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In the United States Patent and Trademark Office

Application Number:	10/692,755
Applicant:	DR. RUSI TALEYARKHAN
Examiner:	DR. RICARDO PALABRICA
Art Unit:	3663

February 27, 2009

FILING OF THE APPEAL BRIEF

VIA FAX 571 273 8300
Assistant Commissioner of Patents
Washington, DC 20231

Sir,

The appeal brief for the Appeal to the Board of Appeals for the above application is attached and contains 76 pages.

Very respectfully,

Dr. Arjuna I. Rajasingham
Chairman & Chief Executive
MMILLENNIUMM ENERGY CORPORATION

Att:
Appeal Brief 76 pages

Applicant: Rusi Taleyarkhan

Application number: 10/692,755

Filing Date: 10/27/2003

Title of Invention: Methods and Apparatus to induce D-D and D-T reactions

Examiner: Rick Palabrica

Art Unit: 3663

Title: APPEAL BRIEF

(B) Table of Contents page(s);

(C) Real party in interest page(s);

MMILLENNIUMM ENERGY CORPORATION

MMILLENNIUMM GROUP INC.

DR. RUSI TALEYARKHAN

(D) Related appeals and interferences page(s);

NONE

(E) Status of claims page(s):

Claims:

1.(Withdrawn).

2.(Withdrawn)

3. (Withdrawn)

4. (Withdrawn)

5.(Withdrawn

6.(Withdrawn)

7.(Withdrawn)

8.(Withdrawn)

9. (Withdrawn)

10.(Withdrawn)

11.(Withdrawn)

12 .(Withdrawn)

13. (Withdrawn)

14. (Withdrawn)

15. (Withdrawn)

16.(Withdrawn)

17.(Withdrawn)

18. (Withdrawn)

19. (Withdrawn)

20.(Withdrawn)

21. (Withdrawn)

22. (Cancelled)

23. (Cancelled)

24. (Cancelled)

25. (Cancelled)

26. (Withdrawn)

27. (Cancelled)

28. (Cancelled)

29. (Cancelled)

30 (Cancelled)

31 (Cancelled)

32 (Cancelled)

33 (Cancelled)

34. (Rejected)

35. (Rejected)

36. (Rejected)

37. (Rejected)

38. (Rejected)

39. (Rejected)

40. (Rejected)

41. (Rejected)

42. (Rejected)

43. (Rejected)

44. (Rejected)

45. (Rejected)

46. (Rejected)

47. (Rejected)

(F) Status of amendments page(s);

The applicant filed an amendment to claims 34 and 47, to correct the inadequate antecedent between claim 34 and Claim 44, and to conform to an elected species (Method) in claim 47. Claim 48, was added to address the comments by the examiner with regard to an optional step in the claimed methods of the invention. A grammatical error in claim 34 was also corrected.

The applicant understands that the amendments will not be entered.

Affidavits filed were not acknowledged by the Office. New Affidavit has been filed.

34. (Currently amended). A method for producing thermonuclear nuclear fusion, comprising the steps of: providing a working liquid enriched with <u>molecules comprising</u> isotopic D or T atoms ~~comprising molecules~~; placing at least a portion of said liquid into a tension state, a maximum tension in said tension state being below the cavitation threshold of said liquid, said tension state imparting stored mechanical energy into said liquid portion; directing <u>fundamental particles</u> ~~nucleating agents comprising at least one of: neutrons, photons, alpha particles and fission products~~, at said liquid portion when said liquid portion is in said tension state, said nucleating agents having sufficient energy for nucleating a plurality of bubbles substantially filled with vapor from said liquid, said bubbles substantially filled with vapor having an as nucleated bubble radius greater than a critical bubble radius of said liquid; growing said bubbles; and imploding said bubbles substantially filled with vapor, wherein a resulting temperature obtained from energy released from said implosion is sufficient to induce a nuclear fusion reaction of said isotopic D or T atom comprising molecules in said liquid portion.

47. (currently amended) <u>A method</u> ~~An apparatus~~ for producing thermonuclear fusion, comprising <u>the steps of : filling</u> a chamber <u>with</u> ~~containing~~ a high accommodation coefficient liquid; ~~a means for~~ inducing tension in said high accommodation coefficient liquid; <u>directing</u> a nucleating agent comprising at least one of: neutrons, alpha particles, photons and fission products to said chamber; ~~a means for~~ enhancing the size of the nucleated bubbles in tension

to a volume greater than a predetermined volume before inducing controlled implosion; thereby producing thermonuclear fusion.

48. (new) A method of claim 34, wherein the working liquid is de-gassed prior to being put in a tension state.

(G) Summary of claimed subject matter page(s);

Note: The appellant submits that the responses are given in relation to the July 23, 2005 Published Application by paragraph. The line numbers quoted are in relation to the noted paragraphs.

Claim 34.

A method to produce thermo-nuclear fusion in the local environment of vapor bubbles in the body of their parent liquid.

Comprising the steps of:

Step1.

> *"providing a working liquid enriched with molecules comprising isotopic D or T atoms"*

Figure 1 (item 124)

Para. 22 (line 12); Para. 73 (lines 2-3); Para. 76 (lines 2, 3, 8)

Step2.

> *"placing at least a portion of said liquid into a tension state, a maximum tension in said tension state being below the cavitation threshold of said liquid, said tension state imparting stored mechanical energy into said liquid portion"*

Para.15 (lines 3-6); Para.18 (lines: 2-5); Para. 26 (lines 3-7); Para. 178 (lines 1-3).

Step3.

> *"directing fundamental particles , at said liquid portion when said liquid portion is in said tension state, said nucleating agents having sufficient energy for nucleating a plurality of bubbles substantially filled with vapor from said liquid,*

said bubbles substantially filled with vapor having an as nucleated bubble radius greater than a critical bubble radius of said liquid"

Fig.1 (item 150); Fig. 3c; Fig. 6 (item 633)

Para. 15 (lines 8-11); Para. 18 (lines 6-8); Para 21 (lines 1-2); Para. 55 (lines 3-4); Para. 129, Para. 132 (lines 3-7); Para. 166 (lines 1-3); Para 71; Para 176 (1-3).

Step4.

"growing said bubbles"

Fig. 3c

Para 15 (lines 9-11); Para 26 (lines 8-9); Para 33; Para 57 (lines 3, 8-9); Para 58 (lines 1-2); Para 63 (lines 3-5); Para. 64.

Step5.

"imploding said bubbles substantially filled with vapor, wherein a resulting temperature obtained from energy released from said implosion is sufficient to induce a nuclear fusion reaction of said isotopic D or T atom comprising molecules in said liquid portion"

Para 15 (13-17), para 18 (lines 8-11), para 26 (lines 11-14), para 28 (lines 8-11)

Claim 47.

Step1.

"filling a chamber with a high accommodation coefficient liquid"

Fig. 1 (item 124)

Para 66, Para 74, Para 107 (1-4)

Step2.

"inducing tension in said high accommodation coefficient liquid"

Para 15 (3-6), Para 18 (2-5), Para 178 (1-3), Para 74, Para 190.

Step3.

"directing a nucleating agent comprising at least one of: neutrons, alpha particles, photons and fission products to said chamber "

Fig.1 (item 150); Fig. 3c; Fig. 6 (item 633)

Para. 15 (lines 8-11); Para. 18 (lines 6-8); Para 21 (lines 1-2); Para. 55 (lines 3-4); Para. 129, Para 130 (1-4), Para. 132 (lines 1-3); Para 157 (1-4), Para. 166 (lines 1-3); Para 71; Para 176 (2-3).

Step4.

"enhancing the size of the nucleated bubbles in tension to a volume greater than a predetermined volume before inducing controlled implosion"

Fig. 3a, Fig. 3c

Para 64, Para 67, Para 72 (lines 8-15), Para 120, Para 133.

(H) Grounds of rejection to be reviewed on appeal page(s);

1. Whether claims 34 -46 are unpatentable under 35 U.S.C. 101 for lack of utility

2. Whether claims 34 -46 are unpatentable under 35 U.S.C. 112, first paragraph, as failing to comply with the enablement requirement.

3. In claim 34 "placing at least a portion of said liquid into a tension state, a maximum tension in said tension state being below the cavitation threshold of said liquid." , whether there is adequate description or enabling disclosure as to how and in what manner one can determine: a) that a portion of the liquid is in the so-called tension state; b) the maximum tension in a portion of the liquid in a tension state; and c) that the maximum tension is below the cavitation threshold of the liquid.

4. In Claim 34 "imploding said bubbles substantially filled with vapor." whether there is either an adequate description or enabling disclosure as to how and in what manner one: a) can determine when a bubble has been substantially filled with vapor; b)identify which of the bubbles that are allegedly substantially filled with vapor; and c) how many of these bubbles to implode to induce a nuclear fusion reaction.

5. In Claim 42 "synchronizing neutron impact with a location in said liquid having a predetermined liquid tension level." whether there is either an adequate description or enabling disclosure as to how and in what manner one: a) can determine the occurrence of an impact of the neutron with the pre-tensioned liquid; b) synchronizes the neutron impact with a location in said liquid; c) determines which specific location to direct the impact of the neutron.

6. In claim 34, whether the deletion of the degassing step is the addition of new matter.

7. In Claim 44, whether the recitation of "said fundamental particles" in lines 1 and 2 results in an insufficient antecedent basis for this claim.

8. In claim 46, whether the term "high accommodation coefficient liquid" is a relative term which renders the claim indefinite. As the term "high" which is not defined by the claim, and the specification does not provide a standard for ascertaining the requisite degree, whether

one of ordinary skill in the art would not be reasonably apprised of the scope of the invention.

9. In claims 34, 35, 37-40, 44, 45, whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934)

10. In claim 36, whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934) with regard to heat exchangers.

11. In claims 42 whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934)

12. In claims 34, 35, 37-40, 44, 45 whether under 35 U.S.C. 102(b) are anticipated by Lipson et ai., "Initiation of fusion reactions in media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992) .

13. In claims 36 whether under 35 U.S.C. 102(b) are anticipated by Lipson et ai., "Initiation of fusion reactions in media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992) .

14. In claims 42 whether under 35 U.S.C. 102(b) are anticipated by Lipson et ai., "Initiation of fusion reactions in media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992) .

15. Whether claim 41, is patentable over either Margulis or Lipson.

16. Whether claim 43 and 46, are patentable over either Margulis or Lipson, in light of Didenko et al.

17. Whether the duplicate claim 34 vs 44 can be overcome with the proposed amendment.

18. Whether Claim 47 is rejected as directed to a non-elected invention.

(I) Argument page(s);

1. Whether claims 34 -46 are unpatentable under 35 U.S.C. 101 for lack of utility

The disclosure states that the invention produces excess neutrons and Tritium as the consequence of thermo-nuclear fusion. Affidavit from Xu. replicates this phenomenon in independent experiments.

References in disclosure:

1. Figs. 3e, 8, 10, 11, 12,13,14;

2. Para. 17;

3. para 24(line1);

4. para 58(line10);

5. para 94 (lines 7-8);

6. para 116(line1);

7. Para 121 (line 3);

8. Para 208;

9.Para 219;

10. Para 222;

11. Para 226;

12. Para 227.

The Utility of Tritium and neutron sources are well established in the background art but also noted in the disclosure in para 24 of the published application, and in Xu's affidavit (para. 8).

2. Whether claims 34 -46 are unpatentable under 35 U.S.C. 112, first paragraph, as failing to comply with the enablement requirement.

In general, the fusion of deuterium(D)-deuterium(D) atoms is unequivocally established in the literature (Gross, 1984) to lead to one of two almost equally probable nuclear reactions. These are:

- The production of a 1.01 MeV tritium (T) nucleus and a 3.02 MeV proton.
- The production of a 0.82 MeV helium-3 (^{3}He) nucleus and a 2.45 MeV neutron.

For the thermonuclear bubble fusion system, the tell-tale signatures of the event involve the measurement of 2.45 MeV neutrons which must be time-correlated with the time of bubble implosion (i.e., when the conditions are compressed and hot and light flashes are generated), the generation of gamma photons commensurate with neutron interactions with structural atoms, together with the generation of T nuclei at rates that are similar in rate to that for neutron production.

The Appelant submits the following to establish probity and enablement.

I. In acoustic inertial confinement bubble nuclear fusion experiments (Taleyarkhan et al., 2002, 2004, 2006), all of which used the teachings of 10/692,755 for enablement, the evidence for D-D fusion includes the following key findings of fact:

1. A statistically significant (4 to 5 Standard Deviations) production of tritium nuclei [Science (2002) – Fig. 3; Phys.Rev.E (2004)-Fig.11];
2. A statististically significant (4 to 25 Standard Deviations) number of 2.45 MeV neutrons [Science(2002)-Fig.4; Phys.Rev.E (2004)-Fig.8; Phys.Rev.Ltr (2006)-Fig.4];
3. An approximately equal number of D-D neutrons and T nuclei produced during any given experiment [Science(2002); Phys.Rev.E (2004)];
4. The generation of D-D neutrons time correlated with sonoluminescence (SL) flashes during deuterated bubble cluster implosions [Science(2002)-Fig.5; Phys.Rev.E (2004)-Fig.7];
5. The subsequent (to neutron and SL) emission of statistically significant quantities of gamma rays due to D-D neutron capture in hydrogen and other atoms of surrounding structures and in the detector; the ratio of gammas to neutrons being about 0.05 to about 0.15, and the energy of the gamma rays being ~ 2 MeV as to be anticipated [Phys.Rev.E (2004)-Figs.9,10];
6. The attainment of null results (i.e., no neutron, gamma or tritium emissions) for corresponding control experiments under identical conditions but with the *only variation being change of the D atoms in test liquids to H atoms* [Science (2002), Phys.Rev.E (2004), Phys.Rev.Ltr (2006);
7. The consistency of the experimentally-observed results of neutrons and tritium with theory which, after considering all key physical phenomena associated with growth and implosion dynamics, reveal and predict conditions required for thermonuclear fusion (i.e., 1000+ GPa compression pressures and ~ 10^8 K plasma states) to occur only under the conditions of successful experiments. The same theoretical framework predicts non-attainment of such conditions for non-ideal thermal hydraulic conditions, as well as for low-accommodation coefficient fluids such as heavy water for similar experiment

conditions – an aspect which is consistent with experimental findings, [Phys. Fluids (2005)-Fig.13, Science (2002)-Fig. 6];

8. The verification and confirmation of the neutron and tritium emission data by unaffiliated groups [Nucl.Engr.Design (2005); NURETH-11 (2005); Trans.Amer.Soc.(2006); Int.Fus.EnergyMtg.(2006); Bugg Report (2006); Public Demonstration Testomonials (2006)];
9. The consistency of neutron emission spectra from 5 separate reports with validated nuclear infrastructure methodologies utilizing state-of-art Monte-Carlo 3-D nuclear particle transport simulation tools (MCNP5 and SCINFUL) developed under U.S. DoE sponsorship at Los Alamos National Laboratory and Oak Ridge National Laboratory – as evidenced in Nucl. Engr. Des.(2008) – **Figs. 6, 7, 9, 11**]; and,
10. Testimonials of successful demonstrations on two separate occasions to collection of industry, government and academic bodies [IDI testimonials, 2006)].

II. Three affidavits confirming replications of the invention by three un-related and un-connected scientist, each of ordinary skill in the Art. These three Affidavits have been submitted and are of record (Please see Evidence appendix) .

The detailed Affidavit of Dr. Xu (para. 3) defines an independent replication of the invention enabled by the disclosures of 10/692,755, in a different location and organization with independently assembled apparatus.

III. The following evidence is further theoretical and experimental support for enablement of the invention. The examiner rejects this evidence as the results were published after the filing date.

A. Three independent academic papers defining the results obtained in replication experiments (corresponding to Affidavits of II. above) .

Three independent replications of published sonofusion results (Nuclear Engineering and Design journal paper, Vol. 235, pp.1317-1324 by Xu et al., 2005; Archives of Trans. American Nuclear Society, Vol. 95, pp. 736-737, by Forringer et al., 2006; Le Tourneau University, Texas, Press Release, 2006; and the Bugg, W confirmation report dated June 9, 2006 to Purdue University of 2006) of the present invention. Proof of reproducibility and repeatability and confirmation of successful fusion signals attainment following the apparatus and operations of this 10/692,755 Application from published documents were reproduced for the examiner.

These are three successful replications of the invention as filed. These replications used the same methods and design of apparatus of the present invention. (Section II. presents affidavits

of these successful replications). Therefore it provides *additional* clear probity for the present invention.

The appellant submits that nothing in the observable ambient universe that could affect this experiment is known to have changed between the date of filing and this duplicate experiment, and the replicators were of ordinary skill in the Art, and therefore the results provide *additional* clear probity for the invention.

B. The theoretical foundation for super-compression-induced thermonuclear fusion for the experimental conditions of the method used for the current application. This theoretical foundation takes into account all relevant physics and chemistry of the condition. It has passed worldwide peer reviews and validated by experts as being on sound theoretical foundations and published in the prestigious journal Physics of Fluids (Nigmatulin et al., 2005). This theoretical foundation when applied specifically to the method of the present invention confirms thermonuclear conditions (see Fig. 13 of the paper by Nigmatulin et al., 2005 – Physics of Fluids, Vol.17, 107106, 2005) with temperatures and pressures reaching in the range of 10^8K, and 1000+ Mbar, respectively – convincingly thermonuclear fusion conditions.

This is a theoretical foundation for super-compression-induced thermonuclear fusion for the experimental method and apparatus of the present invention. Published in a peer reviewed Journal. This theoretical result *by design* addresses the methods and apparatus of the present invention.

The appellant submits that the theoretical result by design considers the apparatus and method of the present invention and therefore the time of publication of the results do not affect the additional probity and enablement that this theoretical study provides.

C. Findings (Fig. 7c) in the premier journal Physical Review E, Vol. 69, 036109-1 to 11, by Taleyarkhan et al., 2004 that demonstrates experimentally that D-D fusion neutrons of 2.45 MeV in energy as required for thermonuclear fusion are emitted in a time –correlated manner with the emission of sonoluminescence (SL) light flashes demonstrating that the fusion reactions are occurring under hot, compressed conditions for the method and apparatus of this present invention application.

This is an experimental study reported in a reputable peer reviewed Journal that further supports enablement of the method and apparatus of the present invention for producing 2.45MeV neutrons required for nuclear fusion, in a correlated manner to the emission of sonoluminescense light flashes. The approach uses the *identical apparatus as noted in the invention* with the *exception of more sophisticated neutron detection approaches to get an even better statistically significant result*.

With regard to this support for probity and enablement, the examiner argues further, that D-D reactions were an non elected species and therefore this result is irrelevent. (The D-D reaction case was a non elected species with traverse) However, the Appellent submits that even if the examiner limits consideration to the elected part of the invention, a D-D reaction envelopes the conditions for a D-T reaction and provides for the record art that establishes factual

experimental underpinnings. (reference: "Gross., R. A., 1984 "Fusion Energy" John Wiley & Sons.) Therefore, the applicant submits that the D-T reactions will occur if conditions for D-D reactions are provided as indicated in the Response of 2008-5-21 as experimental evidence of this reaction phenomenon.

Therefore in this result is further support of probity and enablement as nothing in the observable ambient universe that could affect this experiment is known to have changed between the date of filing and this duplicate experiment.

IV. Furthermore, the applicant has provided in the Appendix, yet another *additional* confirmation for the validity of the thermo-nuclear fusion results " Modeling Analysis and prediction of neutron emission spectra from acoustic cavitation bubble fusion experiments" Nuclear Engineering and Design 238 (2008, 2779-2791).

V. Moreover, further support is provided in the paper on theoretical foundations "The Analysis of Bubble Implosion Dynamics" Supplement #2 (Reference 25 in the IDS) and as published in Science: www. Sciencemag.org/cgi/content/full/295/5561/1868/DC1.

3. In claim 34 "placing at least a portion of said liquid into a tension state, a maximum tension in said tension state being below the cavitation threshold of said liquid." , whether there is adequate description or enabling disclosure as to how and In what manner one can determine: a) that a portion of the liquid is in the so-called tension state; b) the maximum tension in a portion of the liquid in a tension state; and c) that the maximum tension is below the cavitation threshold of the liquid.

The appellant respectfully submits that:

i. There exists a tension state for liquids achievable with tensile forces on the target volume of the liquids. For example even in nature mechanical motion of vascular passages of plants lead to liquid in tension. (Reference: Scholander., P. F., "Sap pressure in vascular plants" Science Volume 18, pp 339-345 16 April 1965.)

ii. Therefore a portion of the liquid may be reduced to the tensioned state by applying a tensile force to the container walls that is by design in contact with the liquid. Such a force may be effected by a mechanical device as in the present invention that may be centrifugal force or oscillations of the wall by an electro-mechanical device. Such force enabling by these two phenomena are well established in the background art. The magnitude of the noted force can be increased by design to ensure that the liquid is at a desired level of the tension state.

iii. The specification teaches the regions of the liquid that are in tension as a result of the apparatus design. For example originally filed Specification page 47 line 15-18 and Page 39 lines 19-21. (para [0135] and para [0167] as published).

iv. There exists a cavitation threshold for such tensioned liquids by audible and visible inspection at adequate drive power of the mechanical force in the presence of nucleating particles.

v. The method or apparatus of the invention can achieve and exceed such a cavitation threshold *by design* as in 3.2 above, as a result of 3.3 above.

Therefore the appellant respectfully submits that the enablement requirement is met with the background art.

4. In Claim 34 "imploding said bubbles substantially filled with vapor." whether there is either an adequate description or enabling disclosure as to how and in what manner one: a) can determine when a bubble has been substantially filled with vapor; b)identify which of the bubbles that are allegedly substantially filled with vapor; and c) how many of these bubbles to implode to induce a nuclear fusion reaction.

The appellant respectfully submits that:

i. The background Art is replete with exposition that any fluid will exert a vapor pressure in an adjoining space and therefore such bubbles are substantially filled with vapor of the parent liquid as disclosed. As there are no other liquids in contact with the bubble surface therefore there is no other vapor pressure exerted. Moreover, considering that there is no attempt to intentionally dissolve gases in the parent liquid the resulting partial pressures if any such gases are small, however as the parent liquid at some point may have had a surface open to a gas such as the constituent gases of the atmosphere, there is likely to be some – even minute quantities -- of preexisting dissolved gas in the parent fluid. Therefore the applicant submits that all such bubbles are substantially filled with vapor of the parent liquid.

ii. One or more such imploding bubbles create nuclear fusion as substantiated in the experimental observation results of the disclosure. The nature of bubbles that create nuclear fusion are defined in the Specification Page 18 lines 20-21 page 19 lines 1-4.

Therefore the appellant respectfully submits that the disclosure in conjunction with the background art is enabling.

5. In Claim 42 "synchronizing neutron impact with a location in said liquid having a predetermined liquid tension level." whether there is either an adequate description or enabling disclosure as to how and in what manner one: a) can determine the occurrence of an impact of the neutron with the pre-tensioned liquid; b) synchronizes the neutron impact with a location in said liquid; c) determines which specific location to direct the impact of the neutron.

The appellant respectfully submits that the specification discloses the production of tensioning of the liquid in synchronization with the nucleating particles. Fig 3, Page 21 lines 8-15, Page 25 lines 3-20, of the original Specification.

The nucleating particles are directed in the direction of the chamber and therefore those that reach the liquid during the above tension state are capable of nucleating 10-100nm size bubbles. It is established in the background art that nucleating particles can nucleate bubbles of this size in meta-stable liquids. Reference: Glaser. D. A., Phys. Rev., Vol.87, 665, 1952.

Therefore the appellant respectfully submits that the disclosure in conjunction with the background art is enabling.

6. In claim 34, whether the deletion of the degassing step is the addition of new matter.

The examiner rejects claims 34-46 as he notes that on claim 34, as amended: applicant has deleted the step, "degassing said liquid to reduce a dissolved gas content therein, wherein said dissolved gas is removed using an applied vacuum." Note the following passages in the specification that demonstrate criticality of the degassing step in the exercise of the claimed invention:

"To minimize the effect of gas cushioning during implosive collapse, the working liquid can be degassed, a priori. Alternatively or *in combination,* a *sufficient vacuum state above the working liquid accompanied by induction of gaseous cavitation induced by nuclear particles such as neutrons* or *via use of lasers* or *acoustic horns can be used to reduce the dissolved gas content in the working liquid to limit unwanted gas cushioning." See page* 17, last *paragraph.*

Following degassing of the working liquid, the liquid is tensioned and nucleation of vapor cavities followed by implosion of the same can be initiated. Tensioning the liquid can be provided by a *variety of methods, including an acoustical wave source, an electrostrictive (piezoelectric) source,* a *magnetostrictive source,* a *centrifugal source,* a *focused (pulsed) acoustic energy* or a *venturi based system. Preferably, when an acoustical wave source is used, the acoustical wave source includes an acoustical focusing device, such as* a *parabolic-type reflector* or a *resonant cavity to intensify the acoustic pressure. See page* 17, *last paragraph.*

The appellent respectfully submits that the degassing step is an <u>*optional*</u> step to enhance the operation of the method or apparatus even as stated in the above by the examiner:

> "To minimize the effect of gas cushioning during implosive collapse, the working liquid <u>*can*</u> be degassed, a priori." (emphasis provided)

For example there is no need to de-gass a liquid that is already substantially free of gas.

The applicant therefore respectfully submits that the claim as amended is consistent with the original disclosure which is enabling.

7. In Claim 44, whether the recitation of "said fundamental particles" in lines 1 and 2 results in an insufficient antecedent basis for this claim.

The appellant has amended the claim to be consistent and submits that as amended it is now with claim 34.

8. In claim 46, whether the term "high accommodation coefficient liquid" is a relative term which renders the claim indefinite. As the term "high" which is not defined by the claim, and the specification does not provide a standard for ascertaining the requisite degree, whether one of ordinary skill in the art would not be reasonably apprised of the scope of the invention.

The appellent respectfully submits that the specification makes clear what high and low mean. High accommodation coefficient is stated to be ~1.0 (the maximum) the value associated with organic liquids such as acetone, benzene, tetrachloroethylene whereas, low is stated to be closer to 0 citing the value for water at ~ 0.07 which is not recommended for enhanced fusion induction capability. See for example Specification as filed for experimental results page 16 lines 8-20 and validating theoretical foundations Page 70 lines 14-20, Page71 lines 1-8.

Moreover, the background art has definitions for high accommodation liquids accessible to those with ordinary skill in the art for example. Reference 25 in the IDS of 2003 .

Comparison -Margulis and Lipson with the present invention 10/692,755 for 102/103 rejections

Table I:102/103 rejections COMPARISON: 10/692,755 vs Margulis & Lipson		
Claim	10/692,755	Margulis (M) & Lipson (L)
Operability of invention is demonstrated?	Yes. Evidence presented of operability in major scientific journals per IDS filings.	No. There is no evidence of operability of claims for neither (M) nor (L).
Independently replicated per teachings of application by practitioners with ordinary skill?	Yes. Three signed affidavits submitted, preceded by corresponding technical papers submitted in an IDS.	No.
Independent Claims 34, 47 System on Enablement regarding the material to be fused and environment of the system	ENABLED by D and/or T atoms which are in molecules of <u>vapor of working liquid</u> itself and are located within a resonant acoustic chamber (with transducers positioned outside of the liquid on <u>outside of chamber walls</u>). No deliberate injection or saturation with externally added D and/or T gas and no need for electric field.	**(L)** ENABLED BY Acoustic <u>horn metal tip(s)</u> dipped into D/T hydrogen gas filled liquid Or **(M)** ENABLED BY transducers dipped into liquid and injecting <u>gas bubbles with D;T</u> saturating parent liquid and with the requirement of a constant <u>electric field</u> in the chamber
Independent Claims 34, 47 on Mode of acoustic energy delivery and Control	ENABLED by Co-ordinated, synchronized acoustically induced tension metastability together with incident MeV scale nuclear particles. Delivery of acoustic energy externally to liquid via <u>container</u> only, not to liquid directly.	**(L)** Use Acoustic <u>horn metal tip(s) &</u> **(M)** provide acoustic to liquid; <u>energy imparted to gas-filled bubble</u>(s); NO teaching of use of synchronized external or internal nuclear particles
Claims 34,42: Method for Timing for Generation of and Number of bubbles	ENABLED by Cluster of several hundred <u>liquid molecule vapor bubbles</u> formed on-demand and synchronized in time with the acoustic tension field by known flux of Incident neutrons or other stated nuclear particles per Specification.	ENABLED either with randomly evolved pre-dissolved D/T gas from liquid **(L)** or Deliberately inserted D-T <u>gas bubbles</u> along with Noble Gas (Xe) to saturate liquid by dissolved D/T gas in liquid (M).
Claim 42: Location of bubble(s)	Away from solid liquid interfaces <u>Interior of working liquid</u>	On the solid/liquid interfaces. <u>NOT in interior of working liquid</u>.
Claims 34,42,44: Time-synchronization of acoustic waves with neutron or alpha based nucleation of tensioned liquid?	Yes.	No

Claims 34, 47, (48) Non-condensible gas content of bubbles	Substantially free of gas ~0% gas content desired Specification. Explicitly degassed liquid(claim 48)	~100% (No effort or teaching to degas the liquid)
Claim 47: Liquid Type in terms of accommodation coefficient.	High (~ 1.0) accommodation coefficient type – water or liquid metals.	No such specification or teaching. Cited liquids of L and M are Low (~0.1) accommodation coefficient type – such as water or liquid metals.
Claim 34, 42: External Neutron or pre-dissolved alpha emitter based nucleation of bubbles?	Yes.	Impossible. Fusion neutrons, if generated occur when the liquid is in state of compression and as such it is impossible to use the neutrons from D-D or D-T fusion to nucleate bubbles.
Claim 34, 42: Time-span of bubbles in reaction chamber	Highly Transient; Bubbles are <u>formed on-demand</u> and are vapor (not gas) filled which re-condense within milliseconds as per teaching.	<u>Indefinite and continuous life</u>; bubbles in reaction chamber are deliberately left there till the D and/or T atoms are depleted.

9. In claims 34, 35, 37-40, 44, 45, whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934)

The examiner argues:

- As to claims 34, 35, 37-40, 44 and 45, Margulis discloses a method for generation of high-temperature plasma and generating thermonuclear reactions by providing a liquid enriched with a mixture of deuterium and tritium, creating tension microbubbles containing such mixture by ultrasonic vibrations and thereby generating thermonuclear reactions.
- Applicant has not defined which portion of the working liquid is placed in a maximum tension below the cavitation threshold. Absent such definition, the examiner interprets the term broadly and reads it on any and all portions of the working liquid.
- Accordingly, one can always find a portion of the liquid in Margulis that has such maximum tension below the cavitation threshold.
- As to the claimed "nucleating agents", the thermonuclear reactions in Margulis inherently produce at least neutrons and photons, and these are inherently directed to the tensioned liquid because said particles and said liquid are in the same contained volume of the apparatus.
- As to the bubbles being substantially filled with vapor, applicant has not defined the term substantially filled, and the examiner interprets this term broadly to read on any degree of filling that occupies most of the internal volume of a bubble.
- One can always find a plurality of bubbles in Margulis that is mostly filled with vapor because of the heat produced from the thermonuclear reaction .
- As to the growing of the bubbles and the temperature generated from the system, note page 6, last 2 lines in the English language translation of Margulis.

The appellent respectfully submits that there are fundamental differences between Margulis and the present invention as claimed in Claim 34 and its dependant claims:

i. Margulis requires a liquid under *positive pressure* for their reactions – it is a compressed liquid. Margulis *requires gas insertion* into the liquid for their process. Nowhere in Margulis is there reference to tensioned liquids. (Tensioned liquids have an absolute pressure of less than zero). In fact tensioned fluids cannot support the required seeding of D and/or T enriched and saturated gas bubbles together an inert gas, required for operation of Margulis. In contrast, the present invention requires a tension state as stated in claim 34, but no gas bubbles as required by Margulis.

ii. Margulis is ***enabled*** *by the* *introduction of gas bubbles* *containing D and/or T atoms and an inert gas* to saturate the parent fluid in a constant electric field. The present invention *introduces the target D and/or T atoms by vaporizing the parent liquid.* There is no enablement requirement with gas bubbles in the present invention. Claim 34 and its dependants clearly state the working liquid to be enriched with D and/or T atoms and does not depend on any inserted gases nor the presence of an externally imposed electric field.

iii. Margulis with the gas saturated fluid cannot sustain a tension state. The background art is replete with examples of foaming of liquids saturated with gas as an inherent limitation for tensioning. For example consider the analogy of a gas saturated soda bottle that is opened to atmospheric pressure. Therefore the requirement of a tensioned liquid is not possible in Margulis. Therefore, *tension* micro-bubbles cannot be formed in Margulis. Therefore, for Margulis, even if nucleating particles are present, considering that a tension state is not attained, the conditions for these particles to initiate cavitation bubbles in a tension state in the liquid will clearly not be met.

iv. If thermo-nuclear fusion occurs in Margulis, then neutrons produced will be when the gas bubbles are compressed therefore the liquid will be under positive pressure and not tension. In present invention, a cluster of several hundred highly transient liquid molecule vapor bubbles are formed on-demand synchronized in time with the acoustic tension field by known (external to system) flux of incident neutrons or other stated nuclear particles per Specification. Therefore there is no parallel between the present invention and Margulis on the nucleating agents.

v. If thermonuclear fusion occurs in Margulis, then it is true that there will be soon thereafter, rise in the temperature in the predominantly gas bubble. However, there is *no possibility* of the bubbles being substantially filled with vapor *before* such a thermonuclear fusion reaction occurs – if such a reaction were to occur in Margulis. The bubbles in Margulis are by design filled with a D and/or T enriched gas unrelated to the liquid.

The appelent submits therefore that claim 34, 35, 37-40, 45 are not anticipated by Margulis and should be allowed.

10. In claim 36, whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934) with regard to heat exchangers.

The appellent respectfully submits that there are fundamental differences between Margulis and the present invention as claimed in Claim 36:

Margulis uses two heat exchangers. The first to *heat* the liquid and the second to convect away heat created from a possible thermonuclear reaction by neutrons penetrating a blanket. In contrast the present invention *cools* the liquid to below an ambient temperature as noted in claim 36.

The applicant submits therefore that claim 36 is not anticipated by Margulis on this factor as well.

11. In claims 42 whether under 35 U.S.C. 102(b) are anticipated by Margulis (RU 2096934)

The appellant respectfully submits that there are fundamental differences between Margulis and the present invention as claimed in Claim 42:

The appellant respectfully submits that in Margulis, if neutrons are produced with a possible thermo-nuclear reaction, such neutrons are available only under positive pressure and therefore cannot nucleate bubbles. In contrast with the present invention where the neutrons are utilized during a tension phase of the process. Therefore Margulis does not read on the present invention on this factor as well.

12. In claims 34, 35, 37-40, 44, 45 whether under 35 U.S.C. 102(b) are anticipated by Lipson et al., "Initiation of fusion reactions in media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992).

The examiner states in support of rejection of claims 34-40,42,44 and 45:

- As to claims 34,35,37-40,44, and 45, Lipson et al., disclose a method for creating fusion reactions in media containing deuterium by cavitation. (As to the interpretation of the undefined terms in applicant's claim, the discussion above relating to Margulis applies also to Lipson et al.).

- As to the nucleating agents, Lipson et al. discloses the generation of neutrons (see page 1191, col. 2, last paragraph)

- As to tensioning of the liquid below the cavitation threshold, growth of the bubbles and their collapse, see page 1190, bottom of col. 1 and top of col. 2.

The appellant respectfully submits that there are fundamental differences between Lipson and the present invention as claimed in Claims 34, 35, 37-40,44 and 45:

i. Lipson *is enabled* by a vibrating metal projection within a liquid enriched with D, wherein the metal can absorb the D. the present invention does not require such metal protrusions and the claims noted by the examiner have no reference to such metal protrusions.
ii. Lipson states (pp1191 last para): "It follows that assumptions 1 and 2 regarding the possible generation of neutrons during the collapse of cavitation bubbles, either directly in the D_2O or on the metal surface of the vibrator, *find no support from these results*" . (Emphasis provided) The disclosure by Lipson therefore does not support the examiner's claim.
iii. Lipson speculates that there may be conditions for neutron emission during the growth and collapse of cavitation bubbles in D2O *enabled by* the metal surface of the protrusion or vibrator. The preset invention does not require a metal vibrator.
iv. In Lipson the liquid with cavitation bubbles are at positive pressures and not in a tension state of the liquid as in the present invention.

The appellent submits therefore that claims 34, 35, 37-40, 44, 45 are not anticipated by Lipson. The applicant respectfully submits that this claim should therefore be allowed.

13. In claims 36 whether under 35 U.S.C. 102(b) are anticipated by Lipson et al., "Initiation of fusion reactions In media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992) .

The examiner argues that: As to claim 36, Lipson et al. disclose a cooled vessel (see page 1190, col. 2, "Experimental Apparatus and Procedure".

The appellant submits that Lipson uses a temperature of 30 C ±10 C and cools his apparatus to this range. The present invention may be cooled below ambient as claimed. Any scientific apparatus may be cooled to a required range of optimal performance. The fact that both

apparatus are cooled to their respective optimal temperature ranges does not imply that the present invention reads on Lipson or for that matter any other cooled apparatus.

The appellant submits therefore that claim 36 is not anticipated by Lipson.

14. In claims 42 whether under 35 U.S.C. 102(b) are anticipated by Lipson et al., "Initiation of fusion reactions in media containing deuterium by cavitation," Soviet Physics: Technical Physics 37 (1992) .

The examiner argues that as to claim 42, applicant's claim language, "neutron source" reads on the fusion reactions in Lipson et al. that inherently produce neutrons.

The appellant submits that that if Lipson results in a Fusion reaction the neutrons emitted would be available at a time _after_ it has utility in creating cavitation as in the present invention.

The appellant submits therefore that claims42 is not anticipated by Lipson.

15. Whether claim 41, is patentable over either Margulis or Lipson.

The examiner states in support of rejection of claim 41:

> *Claim 41 is rejected under 35 U.S.C. 103(a) as being unpatentable over either one of Margulis or Lipson et al. The size of the bubble is a parameter that depends upon specific design constraints for the system, e.g., the desired energy density of the bubbles (see page 5 of the English language translation of Margulis). Thus, it would have been obvious to modify Margulis or Lipson et al. where an application requires the claimed size of the nucleated bubbles. Such modification would have been within the knowledge and capability of one of ordinary skill in the art at the time of the claimed invention.*

The appellant respectfully submits that even if it were proper to combine background art where there is no prior art teaching for their combination, no combination of Margulis and Lipson can replicate the present invention as Margulis is *enabled* with gas bubbles inserted into an

unrelated liquid and Lipson is *enabled* with a metal vibrator or protrusion in the fluid, *neither of which are required for the present invention.*

Moreover, even if these enablement requirements for Margulis and Lipson were not present, the methods of both Lipson and Margulis use intentionally gas saturated liquids that result in foaming. Such foaming is governed by the ambient pressures that limit bubble size and simply produce more bubbles of the same size. In contrast the present invention utilizes the tensioned state of the liquid to stretch and grow the nuclear particle seeded bubbles to the required sizes. Therefore the conditions of neither Lipson nor Margulis allow for the growth of bubbles.

The appellant respectfully submits that this claim should therefore be allowed.

16. Whether claim 43 and 46, are patentable over either Margulis or Lipson, in light of Didenko et al.

The examiner states in support of rejection of claims 43 and 46:

> *Claim 43 and 46 are rejected under 35 U.S.C. 103(a) as being unpatentable over either one of Margulis or Lipson et al. in view of Didenko et al. (Nature 418,7/25/02). Margulis or Lipson et al. disclose(s) the applicant's claims except for the organic liquid. Didenko et al. teach that organic liquids are advantageous for processes involving cavitation because of their very low volatility (see page 4, last full paragraph).*
>
> *Therefore, it would have been obvious to one having ordinary skill in the art at the time the invention was made to modify the method, as disclosed by Margulis or Lipson et al., by the teaching of Didenko et al., to use organic liquids (which have high accommodation coefficients) for the cavitation liquid, to gain the advantages thereof (i.e., low volatility), because such modification is no more than the use of a well known expedient within the art.*

The appellant respectfully submits that even if it were proper to combine background art where there is no prior art teaching for their combination, no combination of Margulis and Didenko or Lipson and Didenko anticipate the present invention.

iii. Margulis is *enabled* with gas bubbles inserted into an unrelated liquid. Using an organic liquid as recommended by Didenko does not remove the enablement requirement of Margulis.

iv. Lipson is *enabled* with a metal vibrator or protrusion in the fluid. Using an organic liquid as recommended by Didenko does not remove the enablement requirement of Lipson.

v. Didenko (July 2002) is preceded by the priority dates of the present application and is therefore not an item of background art (or prior art).

The applicant respectfully submits that these claims should therefore be allowed.

17. Whether the duplicate claim 34 vs 44 can be overcome with the proposed amendment.

The appellant submits an amendment to remove this duplicate claim.

18. Whether Claim 47 is rejected as directed to a non-elected invention.

The appellant has amended the claim to be a method claim and therefore within the elected species.

(J) Claims appendix page(s);

Claims:

1. A nuclear fusion reactor, comprising: a) a reactor chamber for holding a working liquid molecules, said working liquid molecules including at least two nuclei of heavy isotopes of hydrogen; b) structure for placing at least a portion of said liquid into a tension state, said tension state being below a cavitation threshold of said liquid, said tension state imparting stored energy into said liquid portion; c) a nuclear cavitation initiation source for nucleation of at least one bubble from said tension liquid, said bubble having as an nucleated bubble radius being greater than a critical bubble radius of said liquid; d) a pressure field source of growing said as nucleated bubble to form at least one expanded bubble; and e) a pressure field for imploding said expanded bubble, wherein following implosion of said expanded bubble a resulting temperature sufficient to induce at least one nuclear fusion reaction is provided to said liquid.

2. The reactor of claim 1, wherein said structure for placing said liquid under tension comprises and acoustical wave source.

3. The reactor of claim 1, wherein said structure for placing said liquid under tension comprises an acoustical wave source.

4. The reactor of claim 2, wherein said acoustical wave source includes an acoustical wave focusing device.

5. The reactor of claim 1, wherein said structure for placing said liquid under tension comprises at least one centrifugal source.

6. The reactor of claim 1, wherein said structure for placing said liquid under tension comprises at least one magnetrostrictive source.

7. The reactor of claim 1, wherein said structure for placing said liquid under tension comprises at least one piezoelectric source.

8. The reactor of claim 1, wherein said nucleated bubble radius is less than 100 nm.

9 . The reactor of claim 1, wherein a ratio of a maximum radius of said expanded bubbles divided by said nucleated bubble radius is at least 105.

10. The reactor of claim 1, wherein said nuclear source comprises at least one selected from the group consisting of alpha emitters, neutron sources and fission fragments.

11. The reactor of claim 1, wherein said nuclear source comprises a neutron source.

12 . The reactor of claim 11, wherein said neutron source is an isotopic source having at least one shutter, said shutter opened to synchronize neutron impact with location in said liquid when said liquid is at a predetermined liquid tension level.

13. The reactor of claim 1, wherein said nuclear source comprises an alpha particle source.

14. The reactor of claim 13, wherein said alpha particle source is dissolved in said liquid.

15. The reactor of claim 1, wherein said liquid comprises deuterated acetone.

16. The reactor of claim 1, wherein said reactor further includes a controller for synchronizing delivery of at least one cavitation signal from said cavitation initiation source at a predetermined location in said liquid.

17. The reactor of claim 1, further comprising a structure for cooling said liquid to a temperature below an ambient temperature.

18. The reactor of claim 1, wherein said fusion reaction generates at least one of tritium and neutrons.

19. The reactor of claim 1, further comprising at least one external constraint for restraining said liquid.

20. A nuclear fusion-based electrical power plant, comprising: a) a reactor chamber for holding a working liquid; said working liquid molecules including at least two nuclei of heavy isotopes of hydrogen; b) structure for placing at least a portion of said working liquid into a tension state, said tension state being below a cavitation threshold of said liquid, said tension state imparting stored energy into said liquid portion; c) a nuclear cavitation initiation source for nucleation of at least one bubble from said tension liquid, said bubble having an as nucleated bubble radius

being greater than a critical bubble radius of said liquid; d) a pressure field source for growing said as nucleated bubble to form at least one expanded bubble; e) a pressure field for imploding said expanded bubble, wherein following implosion of said bubble a resulting temperature sufficient to induce at least one nuclear fusion reaction is provided to said liquid, and f) structure for converting energy released from said fusion reaction to electrical energy.

21. A nuclear fusion-based projectile launcher, comprising: a) a reactor chamber for holding a working liquid molecules, said working liquid molecules including at least two nuclei of heavy isotopes of hydrogen; b) structure for placing at least a portion of said working liquid into a tension state, said tension state being below a cavitation threshold of said liquid, said tension state imparting stored energy into said liquid portion; c) a nuclear cavitation initiation source for nucleation of at least one bubble from said tensioned liquid, said bubbles having an as nucleated bubble radius being greater than a critical bubble radius of said liquid; said bubbles a resulting temperature sufficient to induce at least one nuclear fusion reaction is provided to said liquid, and d) a movable constraint bounding said reaction chamber for transferring energy from said fusion reaction to propel a projectile. e) a pressure field for imploding said expanded bubble, wherein following implosion of said bubble a resulting temperature sufficient to induce at least one nuclear fusion reaction is provided to said liquid, and f) a movable constraint bounding said reaction chamber for transferring energy from said fusion reaction to propel a projectile.

22. A method for producing nuclear fusion, comprising the steps of: a) placing working liquid molecules into a tension state, said working liquid molecules including at least two nuclei of heavy isotopes of hydrogen, said tension state being below the cavitation threshold of said working liquid, said tension state imparting stored energy into said working liquid; b) cavitating at least a portion of said tensioned liquid with nuclear particles sufficient to bubble nucleate at least one bubble, said bubble having an as nucleated bubble radius greater than a critical bubble radius of said liquid; c) growing said as nucleated bubble to form at least one expanded bubble using a pressure field; and d) imploding said expanded bubble, wherein a resulting temperature from said implosion is sufficient to induce a nuclear fusion reaction involving said liquid.

23. The method of claim 22, wherein said fusion reaction is a D-D reaction or a D-T reaction.

24. The method of claim 22, further comprising the step of degassing said liquid.

25. The method of claim 22, further comprising the step of cooling said liquid to a temperature below an ambient temperature.

26. The method of claim 22, wherein a centrifugal source is used for said tensioning.

27. The method of claim 22, wherein an acoustical wave source is used for said tensioning.

28.The method of claim 27, further comprising the step of focusing acoustical waves provided by said acoustical wave source.

29 . The method of claim 22, wherein said as nucleated bubble radius is less than 100 nm.

30 . The method of claim 22, wherein a ratio of a maximum radius of said expanded bubbles divided by said as nucleated bubble radius is at least 105.

31 . The method of claim 22, wherein a neutron source is used for generating neutrons, further comprising the step of synchronizing neutron impact with a location in said working liquid having a predetermined liquid tension level.

32 . The method of claim 22, further comprising the step of synchronizing delivery of at least one cavitation initiation signal with a desired tension level in said liquid.

33 . The method of claim 23, wherein said liquid comprises deuterated acetone.

34. A method for producing thermonuclear nuclear fusion, comprising the steps of: providing a working liquid enriched with molecules comprising isotopic D or T atoms ; placing at least a portion of said liquid into a tension state, a maximum tension in said tension state being below the cavitation threshold of said liquid, said tension state imparting stored mechanical energy into said liquid portion; directing fundamental particles , at said liquid portion when said liquid portion is in said tension state, said nucleating agents having sufficient energy for nucleating a plurality of bubbles substantially filled with vapor from said liquid, said bubbles substantially filled with vapor having an as nucleated bubble radius greater than a critical bubble radius of said liquid; growing said bubbles; and imploding said bubbles substantially filled with vapor, wherein a resulting temperature obtained from energy released from said implosion is sufficient to induce a nuclear fusion reaction of said isotopic D or T atom comprising molecules in said liquid portion.

35. The method of claim 34, wherein said thermonuclear fusion reaction is a D-D reaction or a D-T reaction.

36. The method of claim 34, further comprising the step of cooling said liquid to a temperature below an ambient temperature.

37. The method of claim 34, wherein said tension state is a part of a time-varying pressure state including compressive and tensile portions.

38. The method of claim 34, wherein said tension state is a constant tension state.

39. The method of claim 34, wherein an acoustical wave source is used for said tensioning.

40. The method of claim 39, further comprising the step of focusing acoustical waves provided by said acoustical wave source.

41. The method of claim 34, wherein said as nucleated bubble radius is from 10 to 100 nm.

42. The method of claim 34, wherein a neutron source is used for said nucleating, further comprising the step of synchronizing neutron impact with a location in said liquid having a predetermined liquid tension level.

43. The method of claim 34, wherein said liquid is an organic liquid.

44. The method of claim 34, wherein said fundamental particles are selected from the group consisting of alpha particles, neutrons and fission fragments.

45. The method of claim 34, wherein said growing and imploding occurs responsive to an applied acoustical field.

46. The method of claim 34, wherein said liquid is a high accommodation coefficient liquid.

47. A method for producing thermonuclear fusion, comprising the steps of : filling a chamber with a high accommodation coefficient liquid; inducing tension in said high accommodation coefficient liquid; directing a nucleating agent comprising at least one of: neutrons, alpha particles, photons and fission products to said chamber; enhancing the size of the nucleated bubbles in tension to a volume greater than a predetermined volume before inducing controlled implosion; thereby producing thermonuclear fusion.

48. A method of claim 34, wherein the working liquid is de-gassed prior to being put in a tension state.

(K) Evidence appendix pages

Statement of Dr. Yiban Xu

This affidavit is being supplied to state that if called upon, I, Yiban Xu would be competent to confirm as to the accuracy of the following in relation to the experiments on bubble (sono) fusion that I have conducted or participated in:

1. I am making this statement of my own personal knowledge and of my own free will. All of the facts contained in this statement are true.
2. I obtained my PhD in Nuclear Engineering from Purdue University in 2004.
3. The bubble fusion test cell apparatus used for my independent confirmatory studies (Xu et al., 2005) was based on the teachings and design information of the invention document entitled "Methods and Apparatus to Induce D-D and D-T Reactions – Co-Inventors: Rusi P. Taleyarkhan and Colin D. West; US Patent and Trademark Office (USPTO) Application 10/692,755, Filing Date Oct. 27, 2003, Pub.Date: Jun.23, 2005" also used by the Taleyarkhan et al. team as reported in their published papers (Taleyarkhan et al., 2002; Taleyarkhan et al., 2004; Taleyarkhan et al.; 2006).
4. There was no intentional effort to dissolve gases into the test liquid prior to conducting bubble fusion experiments but degassing was conducted per teachings of USPTO 10,692,755.
5. Control experiments were systematically conducted changing only one parameter at a time. This was done to ensure that thermonuclear bubble fusion signals (neutrons and/or tritium) were generated only when the test liquid was deuterated, and when it was undergoing nuclear particle based cavitation with spherically imploding bubble clusters per teachings of USPTO 10,692,755 (Fig.3), all else remaining the same.
6. The well-known required signs of thermonuclear fusion (Gross, 1984) were reproducibly obtained, peer reviewed, and recorded as published in my studies. These included: emission of neutrons of ~2.45 MeV with over 11 standard deviation (SD) statistical significance as shown in Fig. 1a. The appropriateness of the measured spectral shape for my experiments as representing 2.45 MeV neutrons from nuclear fusion was also separately confirmed (Fig. 1b) with a 3-D Monte-Carlo based simulation of my experimental system using well-known and established US-federally sponsored computer codes (MCNP, 2003; Dickens, 1998) together with an independent method based on combination of the well-known MCNP code system with the actually measured and published neutron spectra for my detector type (Lee-Lee, 1998). These results are commensurate with teachings of USPTO 10/692,755 (Fig. 11).

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Statement of Dr. Yiban Xu

7. My experiments also examined for tritium as would be emitted from nuclear fusion, and it was found that the neutron emissions of para. 6 above, were reproducibly accompanied with commensurate emission of tritium with over 4 SD statistical significance (Fig. 2) when bubble implosions were spherical (Fig. 3a) versus elongated in the form of streamers (see Fig. 3b), when such fusion does not occur. When the bubble implosions were spherical (Fig. 3a) they are audible and recordable shock traces which are also accompanied with emission of light flashes (Fig. 4a) thereby, indicating hot, highly compressed conditions for my experiments as would be the case for thermonuclear fusion. Positive nuclear emissions from my experiments indicative of thermonuclear fusion were obtained reproducibly on several different days and also on within the same experimental campaign on a given day. These results are commensurate with teachings of USPTO 10/692,755 (Figs. 3, 10, 11, and 12).
8. Production of neutrons as byproducts of this method and process have significant potential utility, e.g., for interrogation of materials for non-destructive examination of molecular compounds as at airports and cement industries, for radiation therapy, for diagnosis. The same is true for tritium, a special nuclear material of significance not only for the commonly attributed use for maintaining the nuclear stockpile but more so for wide variety of industrial applications as use in airport runway lights, non-electricity based passive lighting, use as a radio-tracer and taggant for molecules in molecular biology research. The utility aspects of a neutron-tritium source are well established (see, e.g., Waltar, 2004).
9. This method of inducing D-D and D-T reactions is furthermore, distinct in that there was no acoustic horn or such vibrator that was dipped into the test liquid during conduct of my reported bubble fusion experiments. In my bubble fusion experiments of the type reported by Taleyarkhan et al. the nucleation of bubbles occurs away from solid-liquid interfaces. Acoustic energy was provided into the test liquid by use of a piezo-electric element epoxied to the outside of the glass wall.
10. In the experiments that I was involved, care was taken to ensure that there were no extraneous sources of nuclear particles that could have given rise to the bubble fusion signatures as reported for my experiments and studies (Xu et al., 2005).
11. The pressure distribution of the bubble fusion test cell (as used for my studies based on teachings of USPTO 10/692,755 produces neutron sensitive cavitation regions away from the solid-liquid interfaces. This is due to the pressure profiles which ensure that bubble nucleation takes place within the bulk of the liquid once the input power is increased above a certain level readily determined experimentally. This attribute is a

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consequence of the pressure profiles in such a design which is an aspect that I have confirmed for myself while conducting oscillating pressure mapping tests also.

12. It is a well-known fact (Gross, 1984) that conditions for D-D fusion subsume conditions for D-T fusion which are ~100 times easier to initiate.

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- Waltar, A., "Radiation and Modern Life," Publisher: Prometheus Books, Inc., 2004

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Statement of Dr. Yiban Xu

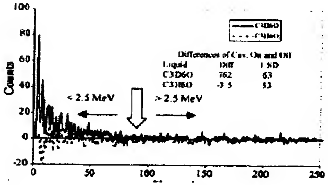

Fig. 1a: Statistically significant (over 11 standard deviations) 2.45 MeV excess neutrons from thermonuclear fusion with neutron seeded cavitation of deuterated acetone(C3D6O) and null results from control experiments with non-deuterated acetone (C3H6O) under identical conditions; confirms teachings of USPTO 10,697,755 (Fig. 11). Fig.1a is excerpted from Xu et al. (2005, *Nuclear Engineering and Design* Journal);

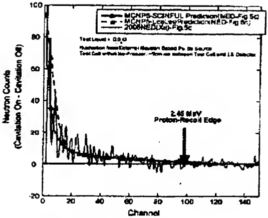

Fig.1b: Independent Numerical Affirmation of D-D Fusion 2.45 MeV neutron spectra with 3-D Monte-Carlo Computer Model simulations of Xu et. al. (2005) experiment using two independent approaches: MCNP-SCINFUL USDoE codes (Dickens, 1988; MCNP, 2003) and MCNP-LeeLee (1998) Measured NE-213 detector Predictions.

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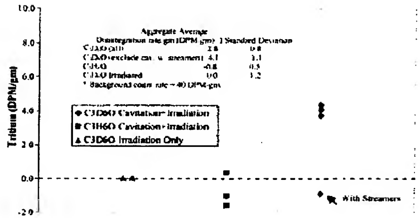

Fig. 2: Statistically significant (4 standard deviations), Reproducible, D-D nuclear fusion based tritium emission with neutron seeded cavitation of deuterated acetone with spherical imploding bubble clusters and null results for all other control experiments commensurate with teachings of USPTO 10,692,755 (Fig.10); Null results are also noted with C3D6O when bubble shapes are non-spherical (streamers); Fig.2 excerpted from Xu et al. (2005).

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Statement of Dr. Yiban Xu

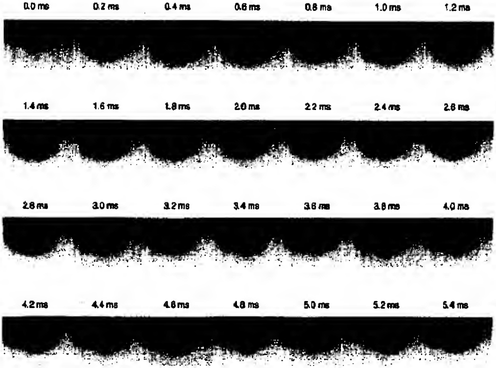

Fig. 3a: Spherical bubble cluster shapes for successful bubble fusion experiments commensurate with teachings of USPTO application 10,692,755 (Fig. 3); Fig.3a excerpted from Xu et al. (2005; *Nuclear Engineering and Design Journal*; Nuclear Reactor Thermal Hydraulics Conference, NURETH-11, 2005).

Yiban Xu [signature]; Date: 02/26/2009

Statement of Dr. Yiban Xu

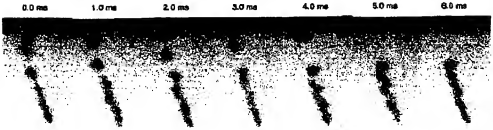

Fig. 3b: Non-Spherical elongated bubble cluster shapes resulting in unsuccessful bubble fusion experiments; Fig. 3b is excerpted from Xu et al. (2005; *Nuclear Engineering and Design* Journal, 2005; Proc. Intl. Nuclear Reactor Thermal Hydraulics Conference, NURETH-11, 2005)

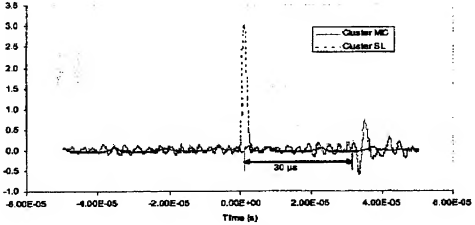

Fig. 4a: SL light flashes for spherically imploding bubbles followed by shock wave 30 µs later for spherically imploding bubbles commensurate with teachings of USPTO 10,692,755 (Fig. 3); Fig.4a is excerpted from Xu et al. (2005, NURETH-11).

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Yiban Xu [signature]; Date: 02/26/2009

Statement of Dr. Yiban Xu

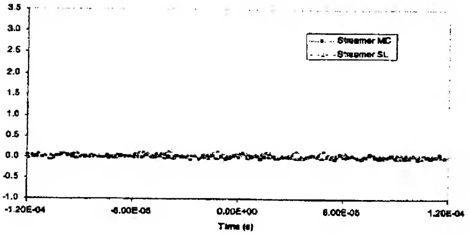

Fig. 4b: Absence of SL light flashes and shock signals for non-spherically imploding bubbles leading to unsuccessful bubble fusion, per USPTO 10,692,755; Fig. 4b is excerpted from Xu et al. (2005, NURETH-11).

Yiban Xu [signature]; Date: 02/26/2009

Affidavit of Dr. JaeSeon Cho

This affidavit is being supplied to state that if called upon, I, JaeSeon Cho would be competent to confirm as to the accuracy of the following in relation to the experiments on bubble (sono) fusion that I have conducted or participated in:

1. I am making this statement of my own personal knowledge and of my own free will. All of the facts contained in this statement are true.
2. I obtained my PhD in Nuclear Engineering in 1999 from Seoul National University and I currently work for FNC Tech. Inc., a high-technology company in S. Korea where I reside.
3. The bubble fusion test cell apparatus used for my studies was based on the design used by the Taleyarkhan et al. team as reported in their published papers [Taleyarkhan et al., 2002; Taleyarkhan et al., 2004; Taleyarkhan et al.; 2006). This is true also for the apparatus in my paper (Cho et al., 2003).
4. There was no intentional effort to dissolve gases into the test liquid prior to conducting bubble fusion experiments.
5. Control experiments were conducted to ensure that bubble fusion signals (neutrons and/or tritium) were generated only when the test liquid was deuterated, and when it was undergoing nuclear particle based cavitation.
6. There was no acoustic horn or such vibrator that was dipped into the test liquid during conduct of my reported bubble fusion experiments. In my bubble fusion experiments of the type reported by Taleyarkhan et al. the nucleation of bubbles occurs away from solid-liquid interfaces. Acoustic energy was provided into the test liquid by use of a piezo-electric element epoxied to the outside of the glass wall.
7. In the experiments that I was involved, care was taken to ensure that there were no extraneous sources of nuclear particles that could have given rise to the bubble fusion signatures as reported for my experiments and studies.
8. The pressure distribution of the bubble fusion test cell as used for my studies (Cho et al., 2004) was based on the Taleyarkhan et al., 2002 design. It produces neutron sensitive regions away from the solid-liquid interfaces. This is due to the induced pressure profiles, which ensure that bubble nucleation takes place within the bulk of the liquid. This attribute is a consequence of the pressure profiles in such a design which is an aspect that I have confirmed for myself while conducting oscillating pressure mapping tests (see Figs. 2 and 6 of Cho et al., 2004). The threshold pressure for neutron based nucleation is readily determined by increasing acoustic power to the point where nuclear particle based cavitation begins.

References Cited Above:

- Cho, J. S., & R. P.Taleyarkhan, Proc. 10th Int. Conf. Nucl. Reac. Thermal Hydraulics, Seoul, S.Korea, October 5-9, 2003.
- Taleyarkhan, R. P., et al., Science, 295, 1868, 2002.
- Taleyarkhan, R.P., et al., Phys. Rev. E, 69, 2004.
- Taleyarkhan, R.P., et al., Phys. Rev. Ltrs., 96, 034301, 2006.

Signed: [signature]

Affidavit of Professor William Bugg

This affidavit is being supplied to state that if called upon, I, William Bugg would be competent to testify as to the accuracy of the following in relation to the experiments and studies on bubble (sono) fusion that I have conducted or participated in:

1. I am making this affidavit of my own personal knowledge and of my own free will. All of the facts contained in this affidavit are true.
2. I obtained my PhD in 1959 from the University of Tennessee-Knoxville, where I served as Head of Physics from 1969 to 1996. I am a Fellow of the American Physical Society and am currently a scientific researcher at Stanford University's SLAC facility.
3. The bubble fusion test cell apparatus used for the confirmatory studies I was involved in (Bugg, 2006) was similar to that used by the Taleyarkhan et al. team as reported in their published papers (Taleyarkhan et al., 2002; Taleyarkhan et al., 2004; Taleyarkhan et al.; 2006).
4. There was no intentional effort to dissolve gases into the test liquid prior to conducting bubble fusion experiments. On the contrary the containers were initially pumped to remove gasses.
5. Control experiments were conducted to ensure that bubble fusion signals (neutrons and/or tritium) were generated only when the test liquid was deuterated, and when it was undergoing nuclear particle based cavitation.
6. There was no acoustic horn or such vibrator that was dipped into the test liquid during conduct of my bubble fusion experiments. In my bubble fusion experiments of the type reported by Taleyarkhan et al. the nucleation of bubbles occurs away from solid-liquid interfaces. Acoustic energy was provided into the test liquid by use of a piezo-electric element epoxied to the outside of the glass wall.
7. In the experiments that I was involved in, I carefully ensured the absence of external sources of neutrons (such as Californium) that could have given rise to the bubble fusion neutron emission signatures as documented in my report (Bugg, 2006).
8. For the bubble fusion confirmatory experiments that I participated in, I noted that spherically-shaped bubbles formed and imploded within the bulk of the liquid away from the walls of containers.

References Cited Above:

- Bugg, W., "Report on Activities on June 6-7 Visit.," Report to Purdue University via email attachment, June 9, 2006.
- Taleyarkhan, R. P., et al., Science, 295, 1868, 2002.
- Taleyarkhan, R.P., et al., Phys. Rev. E, 69, 2004.
- Taleyarkhan, R.P., et al., Phys. Rev. Ltrs., 96, 034301, 2006.

Signed: Wm M Bugg

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Modeling, analysis and prediction of neutron emission spectra from acoustic cavitation bubble fusion experiments

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ABSTRACT

Self-nucleated and external neutron nucleated acoustic (bubble fusion) cavitation experiments have been modeled and analyzed for neutron spectral characteristics at the detector locations for all separate successful published bubble fusion studies. Our predictive approach was first calibrated and validated against the measured neutron spectrum emitted from a spontaneous fission source (^{252}Cf), from a Pu–Be source and from an accelerator-based monoenergetic 14.1 MeV neutrons, respectively. Three-dimensional Monte-Carlo neutron transport calculations of 2.45 MeV neutrons from imploding bubbles were conducted, using the well-known MCNP5 transport code, for the published original experimental studies of Taleyarkhan et al. [Taleyarkhan, et al., 2002. Science 295, 1868; Taleyarkhan, et al., 2004. Phys. Rev. E 69, 036109; Taleyarkhan, et al., 2006a. PRL 96, 034301; Taleyarkhan, et al., 2006b. PRL 97, 149404] as also the successful confirmation studies of Xu et al. [Xu, Y., et al., 2005. Nuclear Eng. Des. 235, 1317–1324], Forringer et al. [Forringer, E., et al., 2006a. Transaction on American Nuclear Society Conference; vol. 95, Albuquerque, NM, USA, November 15, 2006, p. 736; Forringer, E., et al., 2006b. Proceedings of the International Conference on Fusion Energy, Albuquerque, NM, USA, November 14, 2006] and Bugg [Bugg, W., 2006. Report on Activities on June 2006 Visit. Report to Purdue University, June 9, 2006]. NE-213 liquid scintillation (LS) detector response was calculated using the SCINFUL code. These were cross-checked using a separate independent approach involving weighting and convoluting MCNP5 predictions with published experimentally measured NE-213 detector neutron response curves for monoenergetic neutrons at various energies. The impact of neutron pulse-pileup during bubble fusion was verified and estimated with pulsed neutron generator based experiments and first-principle calculations. Results of modeling-cum-experimentation were found to be consistent with published experimentally observed neutron spectra for 2.45 MeV neutron emissions during acoustic cavitation (bubble) fusion experimental conditions with and without ice-pack (thermal) shielding. Calculated neutron spectra with the inclusion of ice-pack shielding are consistent with the published spectra from experiments of Taleyarkhan et al. [Taleyarkhan, et al., 2006a. PRL 96, 034301] and Xu et al. [Xu, Y., et al., 2005. Nuclear Eng. Des. 235, 1317–1324] where ice-pack shielding was present, whereas without ice-pack shielding the calculated neutron spectrum is consistent with the experimentally observed neutron spectra of Taleyarkhan et al. [Taleyarkhan, et al., 2002. Science 295, 1868; Taleyarkhan, et al., 2004. Phys. Rev. E 69, 036109] and Forringer et al. [Forringer, E., et al., 2006a. Transaction on American Nuclear Society Conference, vol. 95, Albuquerque, NM, USA, November 15, 2006, p. 736; Forringer, E., et al., 2006b. Proceedings of the International Conference on Fusion Energy, Albuquerque, NM, USA, November 14, 2006] and also that from GEANT computer code [Agostinelli, S., et al., 2003. Nuclear Instrum. Methods Phys. Res. A 506, 250–303] predictions [Naranjo, B., 2006. PRL 97 (October), 149403] in which ice shielding was also absent.

The results of this archive confirm for the record that the confusion and controversies caused from past reports (Reich, E., 2006. Nature (March) 060306, news@nature.com; Naranjo, B., 2006. PRL 97

Abbreviations: Cf, californium; Ci, Curie; D, deuterium; GEANT, a Monte-Carlo nuclear particle interaction code system; n, neutron; MCNP, Monte-Carlo N-particle computer code; NE-213, trademark of scintillation liquid from Nuclear Enterprises Inc.; LS, liquid scintillation; PNG, pulse neutron generator; PRE, proton recoil edge; PSD, pulse-shape discrimination; Pu–Be, plutonium–beryllium; SCINFUL, scintillator full response computer code; T, tritium; UN, uranyl nitrate; γ, gamma photon.

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(October) 149403] have resulted from their neglect of important details of bubble fusion experiments. Results from this paper demonstrate that ice-pack shielding between the detector and the fusion neutron source, gamma photon leakage and neutron pulse-pileup due to picosecond duration neutron pulse emission effects play important roles in affecting the spectra of neutrons from acoustic inertial confinement thermonuclear fusion experiments.

1. Introduction

In 2006, evidence was presented for a unique, new stand-alone acoustic inertial confinement fusion device that was successfully tested and results published (Taleyarkhan et al., 2006a). Those experiments were conducted with four different liquid types in which bubbles were nucleated without the use of external neutron sources. Four independent detector systems were used [a neutron track plastic detector to provide unambiguous visible records for fast neutrons, a LiI thermal neutron detector, a NE-213-type liquid scintillation (LS) detector, and a NaI gamma (γ) ray detector]. All detector systems measured statistically significant (from 6 to 20+ standard deviations) nuclear emissions for experiments with deuterated benzene and acetone mixtures but not for experiments with heavy water, a finding which validated theoretical predictions (Nigmatulin et al., 2005) of our simulations of the implosion dynamics which indicated that heavy water would not be a good choice for attaining thermonuclear fusion in imploding bubbles. The measured neutron energies from bubble fusion experiments were, as expected, substantially ≤2.45 MeV. Control experiments did not result in statistically significant neutron or γ ray emissions. These observations of neutron emissions in self-nucleated experiments with deuterated benzene-acetone mixtures but not for the controls (i.e., non-deuterated mixtures) have been successfully confirmed (Forringer et al., 2006a,b; Bugg, 2006). In the studies of Forringer et al. and Bugg, the experimental configurations they used were different from that used by Taleyarkhan et al. (2006a,b). The two experimental configurations are shown in Fig. 1a and b . As noted therein, a principle distinguishing factor between the two configurations is the presence or absence of ~3 cm of ice-pack materials acting as thermal shielding around the test cell enclosure. Whereas, in the reported experimental systems of Taleyarkhan et al. (2002, 2004, 2006a,b) the ice-pack shielding was required and present, the same was not true in the experiments conducted by Forringer et al. (2006a,b) and Bugg (2006).

The results of Taleyarkhan et al. (2006a) using the LS detector system offered the highest level of statistical significance of above 17 standard deviations (S.D.). Because of the presence of intervening ice-pack shielding, the published neutron spectrum (Taleyarkhan et al., 2006a) incorporated characteristics that were different from the shape of the neutron spectrum for a monoenergetic 2.45 MeV neutron emanating from the test cell without having to interact with ice-pack shielding. A qualitative discussion was provided (Taleyarkhan et al., 2006b) in response to questions and comments raised from code calculations for the presumed geometric configuration by Naranjo (2006) of the University of California at Los Angeles (UCLA). Unfortunately, the UCLA predictions were made for an incorrectly presumed experimental configuration (e.g., with no ice-packs) and would actually be more applicable for comparisons with the published measured neutron spectra of Forringer et al. (2006a,b) and Taleyarkhan et al. (2002, 2004) rather than those of Taleyarkhan et al. (2006a). Nevertheless, these faulty simulations seeded and caused considerable controversy and confusion (Reich, 2006; Naranjo, 2006).

In 2002 and 2004, evidence was first presented for the neutron spectrum measured during external neutron-based acoustic cavitation experiments (Taleyarkhan et al., 2002, 2004). In these experiments nucleation of bubbles in pure deuterated acetone (C_3D_6O) was achieved using a 14.1 MeV pulse neutron generator (PNG). The test geometry for this study is shown in Fig. 1d. Although the enclosure is similar to that for Fig. 1a, the LS detector was positioned to be within the enclosure as shown with no intervening ice-pack materials. The results of the 2004 studies reported by Taleyarkhan et al. (2004) were successfully confirmed in studies reported by Xu et al. (2005) in which they used a different experimental enclosure type as shown in Fig. 1c, and the bubble nucleation was conducted using randomly emitted neutrons from an isotope source. However, as for the self-nucleation bubble fusion reports of Taleyarkhan et al. (2006a,b), in the Xu et al. (2005) studies, their LS detector was also positioned outside the freezer, and as such, a ~3–4 cm of ice layer was also present between the test cell and the LS detector.

The purpose of this paper is to present a comprehensive unifying study for all the reported successful bubble fusion studies with the goal to remedy the unfortunate controversies and confusion resulting from the misguided simulations for incorrect experimental configurations as reported in the literature (Reich, 2006; Naranjo, 2006), as well as due to the omission of important effects such as pulse-pileup and gamma photon leakage. For completeness, we have conducted simulations of successful published studies not only for the self-nucleation experiments, but also, for the external neutron-based experiments.

Questions have also been raised (Reich, 2006) concerning the detection of neutron counts in channels higher than the 2.45 MeV proton recoil edge (PRE). The present paper includes results of analyses, backed up with experimental evidence, for clarifying the principle mechanisms concerning such occurrence for bubble fusion experiments.

2. Two independent modeling-simulation approaches

In order to evaluate the relative effects on the expected 2.45 MeV spectrum with and without ice-pack shielding we conducted assessments with two independent methods to obtain cross-checks and better confidence for the validity of our predictions. The first approach was to establish a simulation platform similar to that used by UCLA in which results of three-dimensional neutron transport from within the test cell were derived using the USDOE's code system MCNP5 (MCNP, 2003) at the location of the LS detector. This down scattered neutron flux profile was next combined with the USDOE's *Scintillator Full* (SCINFUL) response Monte-Carlo based code system (Dickens, 1988). SCINFUL was developed specifically for predicting the response function of neutron interactions with NE-213 detectors. The second approach we developed was to act as a cross-check to the MCNP5–SCINFUL predictions. It involves directly combining the neutron emission spectra emanating from the experimental system (as derived from MCNP5 simulations) with the published (i.e., directly measured) neutron energy-related pulse-height spectra for an actual 5 cm × 5 cm sized NE-213 detector (viz., of the same size and type as used by Taleyarkhan et al., 2002, 2004, 2006a,b; Xu et al., 2005; also by Forringer et al., 2006a,b). Predictions from both approaches could then be compared with the various published bubble fusion experimental data.

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2.1. Calibration-benchmarking of LS detector with prediction methodology

The SCINFUL code requires the user to provide to it the incoming neutron energy spectrum (e.g., from a known source of neutrons of various energies). A known source could be from a National Institute of Standards and Technology (NIST)-certified isotope source or from an accelerator-based system. Alternately, it could be the prediction from a well-characterized nuclear particle transport code such as MCNP5. SCINFUL utilizes Monte-Carlo techniques and has itself been extensively benchmarked by the developers against a variety of experimental databases for its ability to predict the overall response of a NE-213 LS detector system to incoming neutrons over the energy range 0.5–80 MeV. A known shortcoming is associated with the PRE where detector resolution issues can lead to smearing-related extension of counts to higher channels in an actual detector system but this is not possible to model theoretically since it involves intricacies of individual detector construction and multidimensional issues. In order to gain confidence in the prediction methodology employed for this study it was decided to ourselves calibrate the SCINFUL code predictions for our laboratory's 5 cm × 5 cm NE-213 LS detector using the electronic component train and settings for the published bubble fusion experimental spectra. The comparisons were made for three different neutron sources. The first two were NIST-certified isotope-based neutron-gamma sources: (1) 1 Ci, Pu-Be source emitting ~2×10^6 n/s; (2) ~0.1 mCi, ^{252}Cf source emitting ~10^5 n/s. The second type of neutron source produced 14.1 MeV monoenergetic neutrons from an accelerator device commonly called a PNG and is based on D–T interactions. The emission rate was about 5×10^5 n/s. The NE-213 LS detector was placed ~30 cm from each of these sources and the spectra were obtained with and without

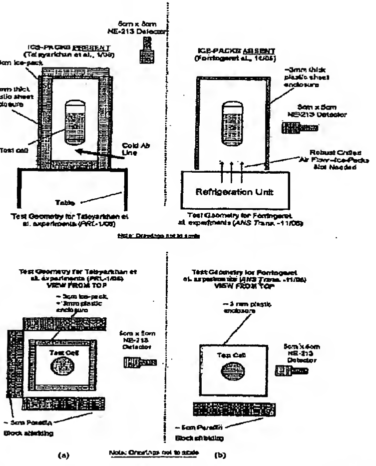
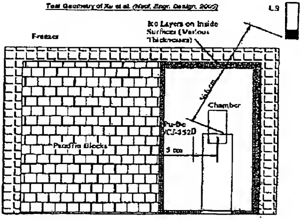
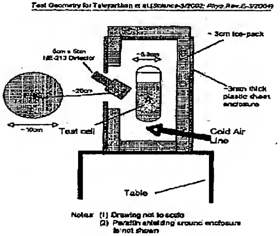


Fig. 1. Experimental geometries of (a) Taleyarkhan et al. (2006a,b) (b) Forringer et al. (2006a,b) (c) Xu et al. (2005) and (d) Taleyarkhan et al. (2002, 2004).



(1c) – Xu et al. (2005)



(1d) – Taleyarkhan et al. (2002, 2004)

Fig. 1. (Continued).

pulse-shape discrimination (PSD). PSD permits rejection of gamma photon-based detector counts from those caused from neutron interactions. At the PSD settings used for the published studies (Taleyarkhan et al., 2002, 2004, 2006a,b; Xu et al., 2005; Forringer et al., 2006a,b) it is estimated that roughly 95% of gamma photons are rejected. Fig. 2a shows the relative spectral emissions for each of these three emission types. Results of the measurements for each of these three sources with and without PSD are shown in Fig. 2b. As noted from Fig. 2b, the monoenergetic 14.1 MeV neutron spectrum displays a sharp reduction in counts at the 14.1 MeV PRE region (channel ~175) but counts still persist and leak into higher channels due to imperfect detector resolution. Since a 14.1 MeV D–T accelerator does not generate gamma photons, the vast majority of counts are neutron driven. For a Pu–Be source, as noted from Fig. 2a, the neutron energies are not monoenergetic but spread out over a large range (0.1 MeV–~10 MeV; the average energy is in the 4 MeV range with a tail towards 11 MeV at which the intensity drops close to zero. Importantly, a Pu–Be source also emits a strong 4.4 MeV gamma photon (Knolls, 1999), roughly at the same rate as for neutron emission; however, unlike the neutrons which are spread out in energy, the gamma photon is monoenergetic due to which, per expectations, we note in Fig. 2b a noticeable jump in the combined neutron-gamma (i.e., without PSD) spectrum around channel 90. As is also seen from Fig. 2a, for the ^{252}Cf isotope-based source, the neutrons are emitted from spontaneous fission with a peak intensity at ~0.8 MeV, with an average spectrum energy of ~1.98 MeV, and with a long tail extending through ~12 MeV where the intensity drops close to zero. ^{252}Cf also emits about three times more

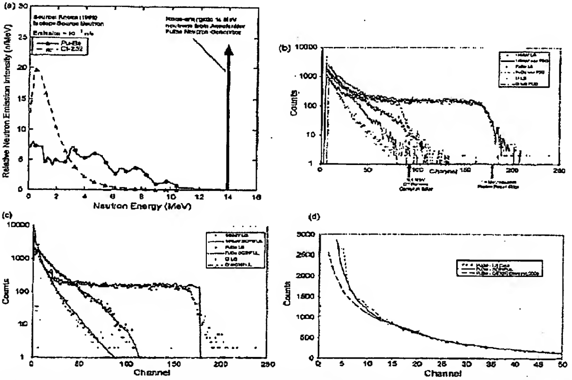


Fig. 2. (a) Spectral shapes of neutron emission intensity vs. energy for various sources used for calibration studies. (b) Measured pulse-height neutron–gamma spectra using 5 cm × 5 cm NE-213 LS Detector with (symbols) and without (lines) pulse-shape-discrimination (PSD; with isotope (^{252}Cf, Pu–Be) and 14 MeV monoenergetic neutron from PNG. (c) SCINFUL Code predictions vs. measured neutron spectra with 5 cm × 5 cm NE-213 LS detector (with PSD). (d) SCINFUL and GEANT code predictions vs. measured neutron spectrum from a Pu–Be neutron source using a 5 cm × 5 cm NE-213 LS Detector. *Note*: Under predictions at lower channels are more pronounced for GEANT calculations—a feature which has also been reported by Patronis et al. (2007).

gamma photons (Knolls, 1999) for each neutron emission and we see this in the measured spectrum of Fig. 2b.

The 14.1 MeV neutron energy and published neutron spectra for the ^{252}Cf and Pu–Be sources were entered as input for SCINFUL code predictions of response for a 5 cm × 5 cm NE-213 detector. This is similar to what one would undertake to do if one were to rely on simulations (e.g., from MCNP5 predictions of down scattered neutron spectra). Results of SCINFUL code predictions for each of the three neutron sources are shown in Fig. 2c alongside the measured LS detector spectra with PSD. As noted therein, the SCINFUL code predictions capture the overall neutron spectral shapes for all three sources with excellent correlation over the entire energy range of ~0.5 MeV at the lower-level cutoff, to ~14 MeV, for the monoenergetic 14.1 MeV neutron spectrum. The coefficient for determination (so-called $R^2 = 1 - SS_{err}/SS_{tot}$; where SS_{err} is the regression sum of squares, and SS_{tot} is the total sum of squares proportional to the sample variance) ranged from ~91% to ~98%. Around the PRE channel (~175) SCINFUL predicts a sharp (almost vertical) rise in counts indicating the response to a head-on collision of the 14.1 MeV neutron with protons in the LS detector liquid. The measured spectrum also shows a significant rise in counts but the shape of this measured spectrum is somewhat smeared as expected for practical detectors (i.e., slanted at ~45° with counts leaking through to channel 250). Such an effect is well-known (Dickens, 1988; Knolls, 1999; Lee and Lee, 1998). This calibration-cum-benchmarking provides good confidence in the ability to predict the spectral response of a 5 cm × 5 cm NE-213 LS detector using a combination of an arbitrary input spectrum of neutron energies together with the SCINFUL code.

At the lower end of the abscissa corresponding to low-angle scattering of neutrons with protons and carbon atoms, a discrepancy between prediction and measurements may be expected as shown in Fig. 2d for comparisons against the measured Pu–Be neutron source spectrum of Fig. 2a. Also presented in Fig. 2d is the published prediction for a Pu–Be source using another Monte-Carlo based code, viz., GEANT (Agostinelli et al., 2003; Naranjo, 2006). SCINFUL and GEANT both tend to somewhat under predict the measured spectrum with the under prediction being greater for the GEANT code simulation as has also been reported elsewhere in the literature for GEANT (Patronis et al., 2007). However, except for some under prediction at lower channels, for most of the energy scale through the PRE channels and beyond, both SCINFUL and GEANT appear to be well-suited for predicting the measured neutron response spectrum for the NE-213 LS detector.

It is also well-known and documented for the SCINFUL code (Dickens, 1988) that detector resolution will vary from detector to detector depending on numerous factors such as light collection efficiency at liquid–photomultiplier interface, age of the detector, etc. Models of detector response for neutron-induced proton recoils therefore, usually model the detector as being one of perfect resolution—which then leads to a sharp increase at the PRE and no counts beyond the PRE (whereas, in actuality a sloping shoulder will be present and counts will occur in channels far beyond the PRE channel number). The capturing of such an effect is at times attempted by Monte-Carlo codes by artificially including a so-called resolution function (see for example, Dickens, 1988) for a given practical detector to force-fit the code predictions at the PRE location to the actual data profile against which it is to be compared in the first instance. Nevertheless, even without engaging in such artifacts, as also demonstrated with our own calibration in this section, the combined MCNP5-SCINFUL code system offers an excellent tool for predicting and studying the essential characteristics of the expected pulse-height spectrum for our experiments for the bulk of the pulse-height spectrum (i.e., for channels below the PRE).

3. Modeling approaches for comparing predictions with measured spectra from acoustic inertial confinement (bubble) fusion experiments

The calibrated SCINFUL code approach which was just discussed was next used to predict the LS detector neutron pulse-height spectrum for comparison against the published spectra. However, instead of using the well-established (i.e., known) neutron energy and spectrum of neutrons from an isotopic or PNG source, the neutron energy spectrum has now to be calculated. A D–D thermonuclear fusion event produces a 2.45 MeV neutron. In a typical bubble fusion experiment, this 2.45 MeV neutron is produced within a deuterated liquid contained in a test cell of approximately 3 cm in radius. Before reaching the LS detector this fusion neutron would necessarily become down scattered in energy as it interacts with intervening atoms of the test liquid, the container wall and shielding materials. It is this downscattered neutron energy spectrum which becomes the source input for SCINFUL predictions of the LS detector pulse-height response, which thereafter, can be directly compared against published experimental data to note how well the published spectra compare with the predicted values. Good agreement provides validation for the neutron source as being that from a D–D fusion event, in much the same manner as the good agreements of Fig. 2c validated the source of neutrons as being from ^{252}Cf, Pu–Be and PNG neutron sources, respectively.

3.1. MCNP5–SCINFUL response simulation

Therefore, as a first step, the transport characteristics of a 2.45 MeV neutron through ~3 cm of test cell liquid, followed by the enclosure wall, were computed using the well-known MCNP5 nuclear transport code (MCNP, 2003) developed by the Los Alamos National Laboratory (LANL). A three-dimensional (3D) model for each of the experimental geometries shown in Fig. 1 was developed. The prediction of the emanated spectrum was used as input for SCINFUL predictions as done before in Section 2. This calculational model is referred to as MCNP5–SCINFUL.

3.2. MCNP5–NE-213 response simulation—an alternate independent approach (MCNP5 neutron spectrum combined piece-wise with measured NE-213 detector response for various neutron energies)

A second modeling approach (refered to herein as "MCNP5–NE-213") was developed to independently compare with the

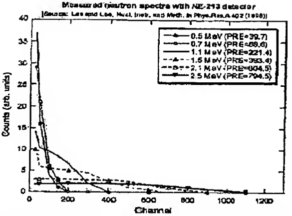


Fig. 3. Measured pulse-height spectra in a 5 cm × 5 cm NE-213 detector (Lee and Lee, 1998) for neutron energies ranging from 0.5 to 2.5 MeV. *Note*: The PRE channel was chosen to be mid-way of the shoulder for each curve (e.g., for 2.5 MeV, the PRE light output channel was deemed to be ~800). Note also that, due to imperfect detector resolution, significant counts occur above the PRE channel.

predictions of the MCNP5–SCINFUL code predictions discussed earlier. This was considered useful for two reasons. First, to cross-check and evaluate that SCINFUL code predictions against experimental data were in line with expectations for the spectrum shape below the 2.45 MeV PRE. The second reason was to help assess how many and how far above the 2.45 MeV PRE one should expect counts due to imperfect detector resolution, a well-known effect (e.g., Dickens, 1988; Lee and Lee, 1998) and also highlighted in established textbooks on the subject (Knolls, 1999). Fortunately, in a relevant study (Lee and Lee, 1998) the authors used a 5 cm × 5 cm NE-213 detector identical in size to the one used in the Taleyarkhan et al. (2002, 2004, 2006a,b), Forringer et al. (2006a,b), and Xu et al. (2005) studies. The Lee and Lee study has published individual pulse-height spectra at six neutron energies ranging from 0.5 MeV to 2.5 MeV. Their results of the measured spectra are replotted in Fig. 3, where the legend for each neutron energy includes the PRE channel number for each of the six neutron energies. As also noted from standard textbooks (Knolls, 1999) we readily note that significant counts can be expected in channel numbers far above the PRE channel for NE-213 type LS detectors. The availability of the six profiles at various neutron energies permits one to combine MCNP5 predictions for incoming neutrons at various energies with these six profiles, thereby acting as a cross-check for the MCNP5–SCINFUL model. That is, instead of relying solely on SCINFUL, we can now also rely on the published experimental response curves at discrete neutron energies of Fig. 3 for an actual detector of the type and size used in the bubble fusion experiments of Taleyarkhan et al. (2002, 2004, 2006a,b), Xu et al. (2005), and Forringer et al. (2006a,b). This model is herein, referred to as the MCNP5–NE-213 model.

However, since MCNP5 predictions for down scattered neutrons are over a continuous energy range, the MCNP5–NE-213 model requires binning. For this reason, the MCNP5 neutron spectrum variation with energy is broken down into six energy groups consistent with the six neutron energies of Fig. 3 to provide the relative proportion of neutrons in each bin. Thereafter, the digitized values of pulse-height spectra of Fig. 3 at each of six energy levels are multiplied by the relative fractional neutron counts (from MCNP5

simulations) in corresponding energy bins and the individual spectra are combined to obtain an overall composite spectrum.

4. Comparison of MCNP5–SCINFUL and MCNP5–NE-213 predictions with self-nucleation and externally nucleated bubble fusion experimental data

Comparison of predictions is shown separately for the self-nucleation experiments and then for the external neutron-based bubble fusion experiments. The more recent self-nucleation experiments are addressed first.

4.1. Comparison with self-nucleated bubble fusion experimental data

In self-nucleated bubble fusion experiments of Taleyarkhan et al. (2006a,b) and Forringer et al. (2006a,b) and Bugg (2006), the nucleation of bubbles was achieved using dissolved uranyl nitrate (a radioactive compound). The test cell and deuterated mixture-cum-uranyl nitrate (UN) contents were modeled using MCNP5 to represent the physical systems described in published documents (Taleyarkhan et al., 2006a; Forringer et al., 2006a,b). 2.45 MeV neutrons were sourced into the middle of the test cell fluid and the transport characteristics through the test liquid, glass walls, and experiment enclosure was assessed using the Monte-Carlo method. The actual experimental geometry also included a layer (~5 cm thick) of paraffin blocks on three sides, and for one side of the enclosure for the experimental configurations of Taleyarkhan et al. (2006a) and of Forringer et al. (2006a,b), respectively. The paraffin blocks served as biological shielding material for experimenters. Fig. 4 displays representative results for the down-scattered neutron energy spectrum in terms of fraction of the total at the NE-213 LS detector face with and without the presence of the 3 cm thick ice-pack material. It is readily seen that the original 2.45 MeV neutron experiences significant down scattering resulting in a range of neutron energies down to thermal energy levels. The extent of down scattering is enhanced significantly with the addition of 3 cm of water (ice-pack) shielding. The displayed results have included all neutrons from 0 MeV to 0.1 MeV in a single energy bin, which accounts for the significantly larger counts for the first energy bin.

The resulting neutron energy spectrum was then used in conjunction with the SCINFUL code for modeling the response of

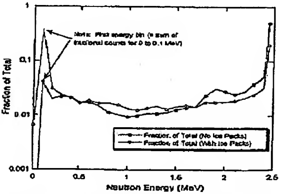


Fig. 4. MCNP5 computed neutron energy distribution for 2.45 MeV neutron after transport through 4 cm of test cell contents and then through 3 cm of ice-pack (modeled as water).

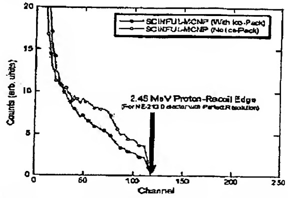


Fig. 5. Monte-Carlo simulation (SCINFUL-MCNP5) prediction of counts vs. light-output (pulse-height) for bubble fusion neutron spectra of Fig. 2 with and without ice-pack shielding.

NE-213 LS detectors to obtain the emanating light pulse-height response spectrum. In so doing, the MCNP5 predicted values for emitted neutron emission spectra of the type shown in Fig. 4 were utilized as inputs for the SCINFUL code to then derive the neutron spectral shapes (Fig. 5) with and without ice-pack shielding. Clearly the spectrum with ice-pack thermal shielding is noticeably different from the spectrum without ice-pack shielding and underscores the importance of accurately including intervening shielding materials. With the ice-pack materials included one notices a largely hyperbolic-like profile (reminiscent of the spectrum from a Cf-252 isotopic neutron source); without ice-pack shielding, the spectrum shape exhibits an anticipated hump starting from the PRE channel region.

Whereas, the spectrum with ice-packs appears qualitatively similar to that measured by Taleyarkhan et al. (as published in Fig. 4 of Taleyarkhan et al., 2006a,b), the calculated light output pulse-height spectrum without ice-pack shielding approximates the general characteristics of the spectrum measured by Forringer et al. (2006a,b), and by Taleyarkhan et al. (2004) and also to the spectrum calculated at UCLA (Naranjo, 2006) where the ice-pack thermal shield material was not included in the computational model. A more comprehensive comparison of data and predictions is provided below.

Next, the MCNP5–NE-213 model was used in which the MCNP5 results (Fig. 4) were binned and combined with the NE-213 LS detector response curves to arrive at the net response spectra of an LS detector for D–D fusion events within the test cell. As done for the MCNP5–SCINFUL model, results were obtained for the two cases with and without ice-pack shielding.

Results from the two approaches can now be compared against the Taleyarkhan et al. (2006a,b) measured neutron spectrum and the various results are shown in Fig. 6 for the experimental case (i.e., with ice-pack shielding). The corresponding results without ice-pack shielding are compared with the experimental measurements of Forringer et al. (2006a,b) as shown in Fig. 7. The reported UCLA predictions using GEANT (Naranjo, 2006) which were conducted without inclusion of intervening ice-pack shielding are also included in Fig. 7. We can now make the following observations:

(i) Ref. Fig. 6: When ice-pack shielding is taken into account, the MCNP5–SCINFUL as well as the MCNP5–NE-213 predictions for

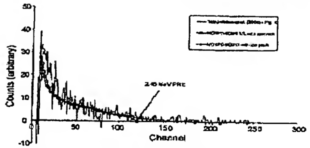


Fig. 6. Predictions of MCNPS-SCINFUL and MCNP5-NE-213 (Lee/Lee) methods vs. measured neutron response spectrum of Taleyarkhan et al. (2006a,b); with ice-pack shielding.

the measured neutron spectrum are consistent with and compare very well with the measured and reported bubble fusion neutron spectrum (Taleyarkhan et al., 2006a,b). For this comparison, the Taleyarkhan et al. measured results at Channel 50 were scaled to equal the predicted value of counts from the MCNP5 based predictions (at the same channel), after which the same scale factor was used for all other channels.

(ii) Ref. Fig. 6: Both MCNP5–SCINFUL and MCNP5–NE-213 predictions are consistent with each other below the 2.45 MeV PRE. Above the 2.45 MeV PRE, the MCNP5–SCINFUL model predicts no counts as would be expected. However, the MCNP5–NE-213 model's detector data-weighted predictions extend ~50 neutron channels above the 2.45 MeV PRE. This is a further confirmation that real-life detectors, with imperfect resolution characteristics, should be expected to allow neutron counts to be collected above the PRE channel. It also provides an important and independent corroboration for, and a valid reason for the excess counts measured (above the PRE) in the neutron spectrum during bubble fusion experiments (Taleyarkhan et al., 2006a,b).

(iii) Ref. Fig. 7: The MCNP5–NE-213 approach which is based on actual measurements offers results which are consistent with the MCNP5–SCINFUL and the public-source GEANT code predictions of UCLA. All three approaches are reasonably close to each other and consistent in terms of overall shape and quantity of counts to be expected below the 2.45 MeV PRE.

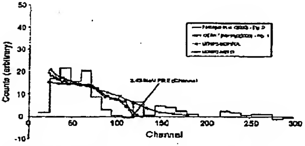


Fig. 7. Predictions of MCNP5-SCINFUL and MCNP5–NE-213 (Lee/Lee) methods vs. measured neutron response spectrum of Forringer et al. (2006a,b) for no ice-pack shielding and scaled GEANT code predictions from Naranjo (2006).

(iv) Ref. Fig. 7: The published bubble fusion neutron spectrum of Forringer et al. (2006a,b) which were obtained without intervening ice-pack shielding is consistent with and compares well with all three prediction schemes. The bubble fusion spectrum of Taleyarkhan et al. (2006a,b), and Forringer et al. (2006a,b) measurements both show counts above the 2.45 MeV PRE and this is also confirmed and predicted by using the MCNP5–NE-213 method.

4.2. Comparison with external neutron nucleated bubble fusion experiments using deuterated acetone

We next turn attention to the earlier bubble fusion experiments of Xu et al. (2005) and Taleyarkhan et al. (2002, 2004). Both of these experimental studies were conducted using pure deuterated acetone as the test liquid. A key difference was that the Xu et al. experiments were seeded with randomly emitted neutrons of various energies from an isotopic neutron source, whereas, the Taleyarkhan et al. studies were conducted using 14 MeV monoenergetic neutrons from an accelerator. Another major difference involved the presence of ~3–4 cm of ice buildup at the freezer walls between the test cell and the LS detector for the Xu et al. (2005) studies, as shown schematically in Fig. 1c, whereas, there was no such intervening ice for the geometry (Fig. 1d) for the Taleyarkhan et al. (2002, 2004) studies.

4.2.1. Comparison against the external neutron nucleated bubble fusion experiments of Xu et al. (2005)

MCNP5 modeling and analysis was conducted for the general geometry of the Xu et al. (2005) studies. Results of the downscattered 2.45 MeV neutrons for various amounts of ice-buildup are shown in Fig. 8a. Fig. 8b presents the variation of fractional down scattering of 2.45 MeV neutrons emitted from the test cell with ice thickness, and one notices the expected exponential-like trend. In Fig. 8a and b we note that due to the exponential downscattering behavior of neutron transport, errors in the actual ice buildup around the nominal 3 cm (~1 in.) value can be expected to remain small. As such, MCNP5–SCINFUL and MCNP5–NE-213 model simulations for the LS Detector response were conducted assuming the ice-buildup thickness of 3 cm.

Results of neutron pulse-height spectra are shown alongside the measured (published) data of Xu et al. (2005) in Fig. 9. It is clearly seen that, over the vast majority of the pulse-height spectrum the comparisons of the MCNP5–SCINFUL as well as MCNP5–NE-213 models are in very good agreement with the data.

4.2.2. Comparison against external neutron nucleated bubble fusion experiments of Taleyarkhan et al. (2002, 2004)

A scoping attempt was also made to compare predictions of the modeling approach against the data obtained with 14.1 MeV externally nucleated bubble fusion experiments of Taleyarkhan et al. (2002, 2004). For the geometry of this experiment shown in Fig. 1d, there was no intervening ice-packing material between the test cell and the LS detector. Due to this aspect one would expect a sharp bump of counts around the 2.45 MeV PRE channel. A complexity arises due to the use of 14.1 MeV neutrons from the PNG for nucleating bubbles. The 14.1 MeV neutron results in a significantly high background due to which, excess counts due to 2.45 MeV neutrons emanating from the test cell, and which are above the 2.45 MeV PRE channel cannot be statistically discriminated from the large 14.1 MeV related background counts. Nevertheless, to decipher first-order effects, MCNP5 was used to model the test cell and detector alone surrounded by the ice-pack walls as shown in Fig. 1d. Due to this aspect, some discrepancies may be expected for the profile of the downscattered neutron energies reaching the LS

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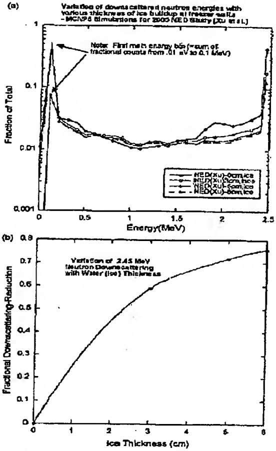

Fig. 8. (a) MCNP5 model predictions for variation of downscattered neutron energies for various thicknesses of ice buildup at freezer walls for externally nucleated experiments of Xu et al. (2005) with deuterated acetone. (b) Variation of fractional downscattering of 2.45 MeV neutrons with ice-thickness for Xu et al. experimental geometry (2005).

detector at the lower channels. Nevertheless, we were mainly interested to note if the principal trends from the MCNP5–SCINFUL and MCNP5–NE-213 model predictions are in general agreement with the published data of Taleyarkhan et al. (2004). Fig. 10 shows the MCNP5 results of downscattered neutrons at the LS detector volume for the geometry of Fig. 1d. Fig. 11 shows the MCNP5–SCINFUL and MCNP5–NE-213 model predictions versus the measurements. The comparisons indeed confirm that the overall trend is well-predicted. The measured spectrum is consistent with that of a 2.45 MeV neutron emitted from a D–D fusion event from within the test cell. In stark contrast to the comparisons against data taken with intervening ice-pack shielding (Fig. 9), when ice-packing is absent, we note a sharp bump in counts around the 2.45 MeV PRE channel in both the MCNP5–SCINFUL model predictions as well as for the measured spectrum of Taleyarkhan et al. (2004).

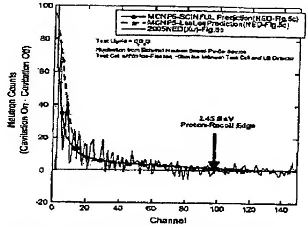

Fig. 9. Predictions of MCNP5–SCINFUL and MCNP5–NE-213 (Lee/Lee) models vs. measured neutron response spectrum (cavitation on–cavitation off) of Xu et al. (2005; Fig. 5c) with ice-pack shielding for external neutron nucleated fusion experiments with deuterated acetone.

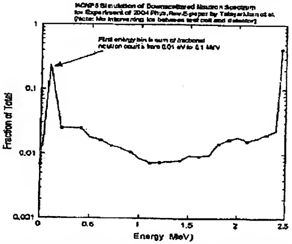

Fig. 10. MCNP5 predictions of down-scattered 2.45 MeV neutrons for Taleyarkhan et al. (2004) with 14 MeV PNG externally nucleated bubble fusion experiments.

5. Experiments and analyses to address the source of measured counts above the 2.45 MeV proton recoil edge (PRE) for bubble fusion

In this section we provide observations and additional experimental data in relation to addressing the excess ("excess" means the additional counts above those from control experiments) counts that are seen above the 2.45 MeV PRE during our bubble fusion experiments using an NE-213 type LS detector. Overall, we have noted that up to ~95% of total excess neutron-gated counts are

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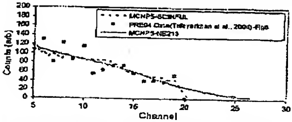

Fig. 11. MCNP5–SCINFUL and MCNP5–NE-213 model predictions vs. excerpted experimental data of Taleyarkhan et al. (2004; i.e., difference of counts from cavitation on minus cavitation off from Fig. 8c) with 14 MeV PNG externally nucleated bubble fusion experiments. *Note*: Counts above the 2.45 MeV PRE channel #21 are difficult to distinguish due to the large 14 MeV neutron background counts of about ~70–80 counts per channel.

obtained below the 2.45 MeV PRE. We have already covered one reason as being due to LS detector resolution, but other factors may also play a role. The source of additional counts above the 2.45 MeV PRE for the LS detector based results are believed to be due to the following phenomena.

5.1. Finite detector resolution

Due to finite detector resolution, the 2.45 MeV PRE turns away from being a sharp rise at the maximum proton recoil energy of 2.45 MeV to a smeared shoulder (Knoll, 1999; Lee and Lee, 1998; Dickens, 1988) as already shown in the previous plots, Figs. 2–7. We estimate the spread to be in the range of up to ~50% light channels above the designated PRE. For our published bubble fusion data during self-nucleated acoustic cavitation, much of the excess counts above the 2.45 MeV PRE will occur within ~50 channels of the PRE channel number. However, beyond the first ~50 channels over the PRE, the finite resolution feature in itself cannot answer why excess counts appear in higher channels and as such, other potential contributors need to be evaluated.

5.2. Imperfect PSD-related γ leakage into the neutron window

In our 1/2006 PRL manuscript (Taleyarkhan et al., 2006a,b), we have pointed out that the PSD system settings were ~93% efficient in terms of gating out gamma photons. This implies that about 7% of gamma photons produced during bubble fusion will necessarily leak into the neutron window. For the geometry of the setup (Fig. 1 of Taleyarkhan et al., 2006a,b), the test cell was enclosed within ice-pack filled enclosure and in addition, there was significant paraffin biological shielding blocks in the vicinity. Neutrons produced from fusion would first downscatter, then interact with Cl atoms in the test liquid to produce ~1.0 MeV to ~1.5 MeV photons, but ultimately, with the abundance of hydrogen atoms around, neutron capture can also result in 2.2 MeV gamma photons. The light pulse-height from 2.2 MeV gamma photons encompasses the entire channel range of the multi-channel analyzer (MCA). Therefore, gamma photons could be readily counted above the 2.45 MeV PRE. As an estimate, using a NaI detector we had reported (Taleyarkhan et al., 2006a) an excess gamma photon count rate of ~0.55 γ/s. A typical experiment lasting about 300 s would collect ~170 gamma photons, of which about 10% (~17) would be able to leak into the neutron window. From a typical excess neutron count population of about 1000 this amounts to about 1.5% of the total population.

5.3. Neutron and gamma counts from fission with uranium in the test cell liquid

For experiments involving self-nucleation using alpha-recoils from uranium decay, the fission of uranium from D–D fusion neutrons may also theoretically lead to counts above the 2.45 MeV PRE channel. The well-established nuclear industry's MCNP5 nuclear particle transport code (developed and maintained at Los Alamos National Laboratory (LANL)) was utilized to assess the neutron spectrum emitted from the test cell. As noted in Fig. 4, a significant fraction of the 2.45 MeV neutrons will be down scattered to lower energies before escaping from surface. About 5–8% of the neutrons were calculated to be scattered down in the energy range of 0–1 eV. Considering the relatively small number density of ^{235}U atoms and also ^{238}U atoms (for which the fast fission threshold is below 2.45 MeV) a preliminary estimate reveals a rather small (<1%) fraction of the total excess neutron counts above the PRE that may result from fission. This phenomenon is not expected to be a significant contributor.

5.4. D–T fusion reactions, or ^{13}C–n interactions

The deuterated test liquid includes a small quantity of tritium, T (^3H) atoms and also a small fraction of the carbon, C atoms will be ^{13}C for which possibilities exist to produce nuclear fusion signatures. However, these contributions are assessed as being negligibly small. Only the D–T reaction may produce 14 MeV neutrons and as such, only a rare, occasional count may appear in the higher channels. The D–T reactions may occur as a result of T atoms being produced during D–D fusion as also from the trace (orders of magnitude lower than that for D atoms) concentrations of T atoms in the procured deuterated liquid itself.

5.5. Neutron pileup

A characteristic feature of acoustic inertial confinement (bubble) fusion is that the neutron emission is not continuous or random but implosion-based, and therefore, will be time-structured. Until recently, this aspect was not revealed as a possibility for excess neutron counts observed above the 2.45 MeV PRE. However, upon reconsideration and based on careful study of our recent theory paper published in the journal *Physics of Fluids* (Nigmatulin et al., 2005) new insights have been derived that appear to dictate that neutron pileup effects in LS detectors of the type used in the reported studies of Taleyarkhan et al. (2002, 2004, 2006a,b), Xu et al. (2005) and Forringer et al. (2006a,b) may indeed play a role in bubble fusion experiments. To further ascertain such an effect, we have conducted a series of experiments and analyses to quantify the relative contribution of neutron pileup (i.e., more than one neutron arriving at the detector within the detector's resolving time) during bubble fusion experimentation.

5.5.1. Experiments and analyses for neutron pileup effect during bubble fusion experiments

The theory of super-compression (Nigmatulin et al., 2005), as applied to our bubble fusion experimentation has revealed that the bubble implosion process leading to D–D fusion for a single bubble in a rapidly imploding cluster occurs within the time span of ~0.1 ps and it will emit about 12 neutrons per bubble implosion. The estimated bubble cluster consisting of ~1000 bubbles is calculated to involve about 40 to 50 bubbles within the interior of the cluster where the amplification in implosion intensity produces thermonuclear fusion conditions. There is some uncertainty involved in terms of estimating the time scale over which the 40–50 bubbles implode but conservatively, we estimate that

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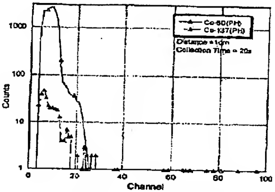

Fig. 12. Calibration spectra with ^{60}Co and ^{137}Cs.

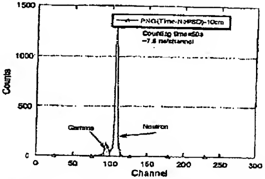

Fig. 13. Fusion (D–T) source PSD neutron-gamma spectrum with LS detector.

they collectively will implode over 100 ps emitting a total of about 200–400 neutrons. This gives us an estimate of the instantaneous rate of neutron emission of up to $\sim 4 \times 10^{12}$ n/s. This is a very high rate indeed and must be accounted for in terms of the possibility and consequence of more than one neutron arriving at the LS detector within the resolving (shaping) time of about ~100 ns (which is considerably longer than the much shorter emission period, which lies in the ps range).

The assessment of possible neutron pileup effects on our LS detector was conducted both with a pulsed neutron source and also via theoretical scoping analyses.

5.5.1.1. *Experiments with a pulse neutron generator (PNG).* We employed a D–T accelerator driven PNG (Model NN-550 from Activation Technologies, Inc.) for assessing whether neutron pileup effects could materialize in our LS detector for neutron pulse rates in the vicinity of expected bubble fusion neutron pulse rates. The PNG system enabled stable operation down to 200 Hz during which neutron pulses are emitted over a time span of ~5–6 μs (FWHM). The LS detector was placed with its face about 10 cm away from the PNG target. The LS detector response to ^{60}Co and ^{137}Cs sources was obtained. It was found (Fig. 12) that the ^{60}Co 1.2 MeV and 1.3 MeV gamma Compton edge is at channel ~15. From published light curves (Harvey and Hill, 1979) it would then imply that the 14.1 MeV PRE would appear around channel 105. With this calibration, the PSD spectrum was obtained and shown in Fig. 13. As previously noted, unlike that for an isotope-based neutron source, the D–T fusion based neutron source results in a much larger fraction of neutrons compared to gamma photons. D–T fusion does not produce gamma photons. Gamma photons are an indirect consequence of fusion neutron interactions with elements of surrounding structures. Based on calibrations with a 1 Ci Pu–Be source it was estimated that the PNG operating with a target voltage of −50 kV and 0.2 kHz would emit $\sim 5 \times 10^5$ n/s, close to the maximum emission level allowed in our laboratory. Since these neutrons are emitted in pulses (~10 μs wide at the base and ~5 μs FWHM) the instantaneous emission rate is much larger at $\sim 5\text{–}10 \times 10^8$ n/s $(\sim 5 \times 10^5 / 5 \times 10^{-6} / 200)$. This formed a baseline for estimating the instantaneous pulse neutron outputs at other target voltages.

Next, neutron-gated pulse-height spectra were obtained at various target voltages ranging from −20 kV to −50 kV. Results of pulse-height spectra are shown in Fig. 14 along with the total neutron counts versus drive voltage in Fig. 15. As expected, the 14.1 MeV PRE is seen to occur around channel #105. The rate of neutron counts increase is more rapid at smaller target voltages and decreases as the target voltage increases. This is in line with well-known $\langle\sigma_v\rangle$ D–T reaction cross-sections (Gross, 1984). Fig. 14 clearly shows that, while insignificant excess counts are measured over the 14.1 MeV PRE at target voltages of less than ~40 kV, the neutron pileup effect becomes noticeably larger for target voltage of −40 kV and above. The variation of the counts above the 14.1 MeV PRE with target voltage, expressed as a percentage is shown in Fig. 15. We see from Figs. 14 and 15 a rapid increase of neutron pileup induced counts above the PRE as the target voltage is increased.

The data shown in Fig. 14 were obtained with a source-to-detector distance of 10 cm compared with 30 cm in the published sonofusion experiments. This would imply a factor of ~10 $[\sim(30/10)^2]$ difference based on solid angle effects, and to get about 3% of total counts above the PRE would require a rate of about 10^{11} n/s. This level of output at a distance of about 30 cm is comparable to (even though smaller than) the estimated $\sim 10^{12}$ n/s neutron emission rates for bubble fusion, thereby, forming a reasonable basis to expect that bubble fusion experiments with detection equipment of the type and configurations used will indeed lead to neutron-pileup related effects giving rise to excess counts above the PRE. The amount of excess may amount to ~5% of the total neutron counts.

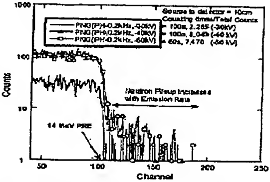

Fig. 14. Pulse-height spectra at various PNG target voltages (*Note:* −50 kV data were taken over 50 s not 100 s).

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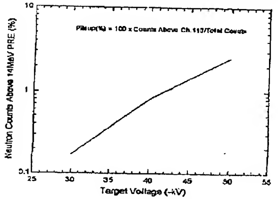

Fig. 15. Neutron pulse-pileup (%) vs. PNG target voltage.

5.5.1.2. Analytic estimation of magnitude of neutron pileup. If N neutrons are emitted during bubble cluster implosion such that they come within the resolving time of the detector, then the probability of a single neutron striking the detector is $N \times f$, where f is the fraction of the solid angle that the detector subtends.

The probability that two neutrons strike the same detector is $N(N-1)f^2$. If the detector efficiency is ε, then the net probability requires that we multiply by ε^2. The LS detector projects an area of about 25 cm^2 so that the solid angle "f" at 30 cm from the test cell becomes 0.0022. Since we have estimated that up to 500 neutrons are emitted per bubble cluster implosion, $N = 500$. Based on known scattering cross-sections for C and H atoms, and the composition of NE-213 liquid, for a 5 cm × 5 cm LS detector, the mean free path for a 2.45 MeV neutron is calculated to be ~5.3 cm. We can then assume that ~60% of all neutrons would receive at least one collision within the LS liquid, which then would offer a theoretical intrinsic efficiency of at least ~50%. Assuming a typical 50% detector (intrinsic) efficiency gives the net probability of the detector receiving two neutrons simultaneously $= 500 \times 499 \times (0.0022)^2 \times (0.5)^2 = 0.3$ or about 30%. This methodology has assumed that each neutron regardless of energy striking the detector will contribute to the "pileup" effect equally. In reality, only neutrons above ~1.3 MeV would be able to have an effect. From MCNP5 assessments the fraction of neutrons above 1.3 MeV is estimated to be ~40% and ~80% with and without ice-pack thermal shielding, respectively. This reduction would bring down the above-estimated 30% down to ~20% [$= 30\% \times (0.8)^2$, without ice-packs] to ~5% [$= 30\% \times (0.4)^2$, with ice-packs], respectively. The approach of this section necessarily encompasses uncertainties, chiefly related to the value of "N", but on an overall basis, it appears in line with and on the order of magnitude of neutron pileup as also witnessed from the experimental observations.

Based on the above, it may be reasonably expected on theoretical grounds that neutron pileup could play an important role in terms of providing excess counts above the 2.5 MeV PRE and the amount to be expected may be in the experimentally observed range of up to ~5%–10% of the total neutron counts.

6. Summary and conclusions

In summary, a comprehensive framework has been developed to model, simulate and understand the 2.45 MeV neutron signature for acoustic inertial confinement (bubble) thermonuclear fusion signature. Both, self-nucleated and external neutron nucleated acoustic (bubble fusion) cavitation experiments have been modeled and analyzed for neutron spectral characteristics at the detector locations for all separate successful published bubble fusion studies. Monte-Carlo neutron transport calculations of 2.45 MeV neutrons from imploding bubbles were conducted, using the well-known MCNP5 transport code, for the published original experimental studies of Taleyarkhan et al. (2004, 2006a,b), as also the successful confirmation studies of Xu et al. (2005), Forringer et al. (2006a,b) and Bugg (2006). NE-213 LS detector response was calculated using the SCINFUL code. These were cross-checked using a separate and independent approach involving weighting and convoluting MCNP5 predictions with published experimentally measured NE-213 detector neutron response curves for monoenergetic neutrons at various energies. This resulted in the formulation of two models: (a) MCNP5–SCINFUL; (b) MCNP5–NE-213 models, respectfully.

The MCNP5-based model was first successfully calibrated and validated against experimental data with an NE-213 based LS detector for three distinct neutron sources: (a) ^{252}Cf; (b) Pu–Be; (c) 14.1 MeV neutrons from a PNG accelerator device. Excellent agreement was demonstrated versus actual experimental data for neutron spectra with PSD.

The impact of neutron pulse-pileup during bubble fusion was verified and estimated with a pulsed neutron generator based experiments and theoretical analyses, both of which provided confidence that an implosion-based bubble fusion process will likely lead to pulse-pileup in the LS detector train. This aspect is consistent with theoretical predictions from our theory paper on super-compression of deuterium atom vapor filled imploding bubbles. Other major contributions and reasons for measurement of nuclear counts above the 2.45 MeV PRE channel were shown to be due to imperfect LS detector resolution around the PRE, gamma photon leakage due to imperfect PSD. The impact of uranium fission and other effects such as D–T or ^{12}C–n reactions were estimated to be of low order in importance.

The MCNP5–SCINFUL and MCNP5–NE-213 models were employed to model and predict the neutron spectra from LS detectors for all of the published data involving both self-nucleation experiments (Taleyarkhan et al., 2006a; Forringer et al., 2006a,b) as well as earlier experiments conducted with external neutron based nucleation experiments (Taleyarkhan et al., 2002, 2004; Xu et al., 2005). A key determinant for the neutron spectral shape was shown to be related to the presence or absence of intervening ice-pack thermal shielding between the test cell and the LS detector. The self-nucleation experiments of Taleyarkhan et al. (2006a,b) and external neutron nucleated experiments of Xu et al. (2005) included the presence of ~3 cm of intervening ice-pack shielding between the LS detector and the test cell. However, the self-nucleated experiments of Forringer et al. (2006a,b) and the external neutron nucleated experiments of Taleyarkhan et al. (2002, 2004) did not include such intervening ice-pack shielding. All four experimental geometries were individually modeled using MCNP5 for deriving the transport characteristics of the 2.45 MeV fusion neutrons from within the test cell for each of the four experiments. The resulting neutron spectrum was next used to derive the LS detector spectral response using the MCNP5–SCINFUL and MCNP5–NE-213 models, respectfully.

The results of modeling-cum-experimentation were found to be consistent with published experimentally observed neutron spectra for 2.45 MeV neutron emissions during acoustic cavitation (bubble) fusion experimental conditions with and without ice-pack (thermal) shielding. Calculated neutron spectra with inclusion of ice-pack shielding are consistent with the published spectra from the experiments of Taleyarkhan et al. (2006a,b) and Xu et al. (2005)

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BUBBLE DYNAMICS AND TRITIUM EMISSION DURING BUBBLE FUSION EXPERIMENTS

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ABSTRACT

Neutron nucleated, transient bubble cluster dynamics has been studied through direct observations of shock wave and sonoluminescence (SL) signals. Confirmatory bubble fusion-related neutron-seeded acoustic cavitation experiments were conducted with deuterated acetone (C_3D_6O) and non-deuterated acetone (C_3H_6O). Tritium emission monitoring was performed systematically by using a calibrated state-of-the-art Beckman LS6500 beta spectrometer for the samples obtained from bubble fusion experiments of non-deuterated and deuterated acetone with and without cavitation. Statistically significant tritium emission was observed during neutron-seeded acoustic cavitation experiments with deuterated acetone, but not for control experiments involving non-deuterated acetone, nor with irradiation alone, thereby confirming reported observations for the occurrence of thermonuclear fusion reactions in deuterium-bearing imploding cavitation bubbles. Thermal hydraulic conditions of bubble implosions leading to robust SL emission are discussed.

KEYWORDS

Bubble fusion, bubble cluster dynamics, tritium counting.

1. INTRODUCTION

Thermonuclear fusion reactions in imploding bubbles (so called bubble fusion) were observed and reported by Taleyarkhan and his coworkers (Taleyarkhan et al., 2002,2004a; Nigmatulin et al., 2004) but so far have not been confirmed by others. Thermonuclear fusion in highly compressed bubbles is possible only when appropriate conditions are provided: high enough (~1000 Mbar) pressure and (~10^7K) temperature and the presence of deuterium (D) atoms which need to be forced close enough, and need to stay together for a sufficient time to permit them to become fused (Gross, 1984). Theoretically, these conditions have been predicted to occur (Moss, 1996; Nigmatulin et al., 2004; Wu, 1993; Taleyarkhan et al., 2004b) and highly depend on bubble dynamics: how these bubbles initiate, grow and implode. Furthermore, recent experiments (Camara et al; 2004) to ascertain temperatures below the surface of SL bubbles have revealed clearly that the emission spectra from the interior resemble those given out by Bremstrahhlung radiation composed of excited plasmas in the 10^6K range. Another study to directly and convincingly demonstrate the existence of plasmas in SL bubbles has recently been published (Flanigan and Suslick, 2005). Based upon these recent

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developments, it is now widely accepted that imploding bubbles can indeed produce extreme states of compression and temperatures.

As is evident, implosions of spherical bubbles produce stronger shock wave compression than aspherical ones; the maximum bubble volume is not only a function of the acoustic pressure amplitude, but can also be affected by the timing of the bubble nucleation (Taleyarkhan, 2004b). Therefore, a comprehensive understanding of bubble dynamics as well as related control variables will be crucial for successful bubble fusion experiments and for future development and optimization of bubble fusion technology.

The process of bubble nucleation, growth and collapse is nonlinear and complicated in general, involving thermal, mechanical, optical, chemical or even nuclear scale phenomena. Depending on the acoustic driving amplitude, a bubble could grow in volume in several acoustic cycles and collapse within one cycle. Huge potential energy accumulated during its growth time can be converted into thermal energy to heat up the bubble's internal contents by shock wave compression. The temperature inside the bubble could be more than 100 million degrees (Nigmatulin et al., 2004) and high enough to accelerate chemical reactions and even cause nuclear fusion reactions. This shock wave continues to propagate in the liquid after the bubble collapses and the evidence can be detected on the chamber walls by an ordinary microphone.

The issue of bubble nuclear fusion thermal-hydraulics becomes even more complicated when a nucleated single bubble grows from ~50 nm by factors of ~100,000 to a large (1000 μm) bubble then implodes and breaks into a cluster of tiny bubbles (Brennan, 1995). These tiny bubbles can stay together as clusters when an acoustic standing wave is applied. From experimental and numerical analyses (Taleyarkhan et al., 2004b) bubble cluster formation can lead to pressure intensification for inner bubbles, causing much higher temperatures and pressures for the bubbles in the center of the cluster than for a single individual bubble. This is attributed to acoustic streaming effects of the shock wave produced by the bubbles along the edge of the cluster (Matsumoto, 2004). Evidently, the assessment of the relative effects of bubble cluster appears crucial for understanding conditions relevant for attaining bubble nuclear fusion, and scale-up of bubble fusion dynamics. This was therefore, attempted for which salient results are presented in this paper.

An important consideration in such experiments to evaluate the occurrence of nuclear fusion involves experimental evidence of key signatures. Notably, for bubble fusion experiments (Taleyarkhan et al., 2002, 2004a) the bubble collapse time is so short and the final bubble size during implosion is so small that any attempts of measuring the variables inside a bubble are extremely difficult, if not impossible. Therefore, indirect approaches must be used to identify the possible nuclear fusion reactions in a collapsing bubble. The well-known D-D nuclear fusion reaction proceeds in two branches of roughly equal probability as (Gross, 1984)

$$D + D = \begin{cases} n + {}^3He \\ p + T \end{cases} \tag{1}$$

The products of D-D fusion reaction are: a neutron (*n*), a proton (*p*), Helium (*He*) and tritium (*T*). Helium (^{3}He) is a non-radioactive gas and it is difficult to detect and the MeV energy protons (due to them being charged particles) can travel no more than ~1 mm through the test fluid and before getting absorbed. On the other hand neutrons (being uncharged particles) can escape from the test cell, and tritium is a radioactive isotope readily detectable using beta-spectrometry. Therefore, neutrons and tritium become the candidates for fusion reaction detection in bubble fusion experiments as reported by Taleyarkhan et al. (2002, 2004a). However, in bubble fusion experiments, it is to be realized that neutron detection can become difficult due to the presence of large gamma ray fields resulting from the neutrons used to seed bubbles. This requires sensitive on-line detection equipment which can distinguish neutrons from gamma rays, and also distinguish neutrons from nuclear fusion from those neutrons used for seeding bubbles from an external neutron source (PNG or isotopic source). Such issues and complexities are non-existent when monitoring for the radioactive isotope tritium.

This paper focuses on reporting investigations on two aspects of bubble nuclear fusion: transient bubble dynamics along with SL light emission, and tritium production. These two topics are presented separately. The first part of this manuscript discusses observations of bubble thermal-hydraulics during the simulated bubble fusion experiments. These observations were obtained in a desktop test apparatus with isotope neutron-seeding of cavitation nuclei in a test cell. The second part provides confirmatory evidence of tritium emission during neutron seeded acoustic cavitation of deuterated acetone, along with evidence of null results from control experiments.

2. EXPERIMENTAL APPARATUS AND APPROACH

The bubble dynamics experiments were performed in a test apparatus (see Figure 1) similar to what was used by Taleyarkhan et al. (2002, 2004a). The test chamber was placed in a chilled light-tight enclosure. A microphone (MIC) was attached to the outside wall of the chamber for shock wave detection (indicative of bubble implosions) for which the low frequency components were filtered out for counting of cavitation rate. A photomultiplier tube (PMT) was placed ~1 cm away from the test chamber for sonoluminescence (SL) light detection. The PMT was powered by a high voltage supply at -2000 volts and its output was first sent to a preamplifier (ORTEC 113) and then to an amplifier (ORTEC 570). The fluid (normal acetone) was driven and experienced positive and negative pressures at a frequency of ~20 kHz by the acoustic wave generated from a PZT ring epoxied on the chamber. An isotope neutron source (Cf-252 0.5 mCi) was used to seed nuclei in the fluid. A high speed video camera (Fastcam 10K) was used to visualize the bubble behavior.

Following the methods reported elsewhere (Taleyarkhan et al., 2002) before conducting bubble fusion experiments the test cell drive amplitude corresponding to about -7bar for nucleation from multi-MeV neutrons was evaluated after degassing. That is, no bubble nucleation would occur at this acoustic drive power over a waiting time of ~ 30s in the absence of the neutron source. Thereafter, after the baseline drive amplitude was doubled to be ~ +/- 15 bars for each of the cavitation runs (as used by Taleyarkhan et al., 2002, 2004a).

It is well-known that tritium is an extremely rare isotope and can only be produced by via nuclear reactions and hence, becomes a powerful indicator for possible thermonuclear fusion reactions during bubble fusion experiments. Tritium can be examined for its presence in the test fluid after the experiment, but this requires access to expensive and sensitive beta spectrometers. Fortunately, as part of the infrastructure we had access to a state-of-the-art beta spectrometer system, the Beckman LS6500™ system at Purdue University, which was similar to that used in the reported bubble fusion studies at Oak Ridge National Laboratory (Taleyarkhan et al., 2002, 2004a). Therefore, we focused on monitoring for tritium emission during acoustic cavitation experiments to confirm the possible occurrence of bubble nuclear fusion. Along with D-D nuclear fusion producing tritium, it is well-known that D atoms in a deuterated liquid can become transmuted to T atoms in the presence of a very high flux of neutrons (as in a commercial power nuclear reactor). Fortunately, in bubble nuclear fusion experiments transmuting D atoms to T atoms by neutron bombardment is a second order effect, a fact which can be readily validated via conduct of control experiments (i.e., experiments conducted to note changes in tritium content of the test liquid by subjecting the test cell to the same experimental neutron fluence used for seeding bubbles, but without acoustic power turned on such that cavitation is not present). Control experiments were also to be performed under identical experimental conditions, but changing only one parameter at a time (e.g., cavitation on vs. off; alternately, change H bearing liquid to D bearing liquid). The control experiments include non-deuterated fluid tests along with cavitation on or off tests. Evidence for thermonuclear fusion reactions (from tritium emission) in a collapsed bubble needs to manifest only for neutron-seeded cavitation in a deuterated fluid. All tests with a non-deuterated fluid or a test with deuterated fluid without cavitation should not lead to tritium production.

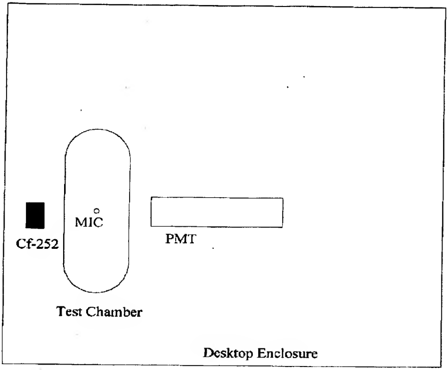

Figure 1: Schematic of experimental apparatus layout (not scaled). Cf-252 – Isotope Neutron Source (0.5 mCi); MIC – Microphone; PMT – Photomultiplier Tube.

3. RESULTS OF BUBBLE DYNAMICS

Following the published approach by Taleyarkhan (Taleyarkhan et al., 2002 and 2004a), the fluid was first properly degassed for about 2 hrs until individual cavitation bubble clusters were achieved. During such evolution, sharp (N-shaped) shock traces were observed on the high-speed digital storage oscilloscope screen coming from the microphone and the PMT. The bubble dynamic behavior has been studied as follows: cavitation visualization by using a high speed video camera (Fastcam 10K), shock wave detection by using a microphone attached on the outside wall of the test chamber and sonoluminescence light emission by using a photomultiplier tube. Typical results are illustrated in the following subsections.

3.1 Cavitation Visualization

Figure 2 displays a typical image sequence of a cavitation bubble cluster of non-deuterated acetone nucleation seeded by neutrons from a Cf-252 isotope source (0.5 mCi of activity) and experienced pressures at ~+/- 17 bars driven by acoustic waves. Note that the images were taken at a speed of 5000 frames per second and 1/20000 s for shutter speed. Since the camera frame speed is smaller than that of the chamber driving frequency, it is believed that the bubble is actually a bubble cluster, which can be verified by quickly turning off the acoustic driving power. The bubble cluster which was otherwise held in place by the acoustic pressure field breaks apart and results in a dispersion of several tiny (~10^2 μm) bubbles. Also, direct numerical simulations for bubble growth using the well established Rayleigh-Plesset formulation indicates that an individual bubble that can reach a maximum of only ~400 μm (Nigmatulin et al., 2002), whereas the size of individual clusters is about 10 times

larger. The images were compensated for the distortion due to the optical deflection from a cylindrical surface and its scale is about 0.083 mm/pixel. The bubble cluster diameters in the first three images at t=0.0, 0.2 and 0.6 ms are about 0.6 , 2.7 and 3.4 mm, respectively. The first appearance of contraction (perhaps because some of the bubbles in the cluster were imploded in this frame) is seen at t=0.8 ms. The cluster size did not vary much after the first contraction and was diffused out after 3 ms.

Figure3 shows another type of cavitation consisting of comet-like streamers. Unlike that of individual bubble clusters, the structure of a streamer appears continuous in space and time: bubbles were formed at one end (bottom end in this figure) and ejected outwards from the other end and could last as long as 10 s. Interestingly, and importantly, it was observed that streamers produce neither distinct shock wave peaks in the microphone nor SL light emission. This is described in the next section.

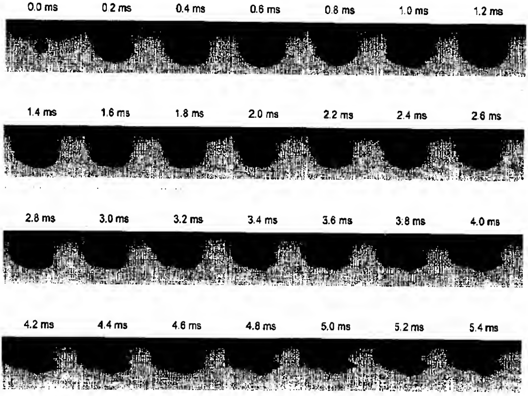

Figure 2: Individual bubble cluster (C_3H_6O, 4 °C, ~+/- 17 bars, 16.7 kPa)

Figure 3: Comet-like streamers (C_3H_6O, 4 °C, ~+/- 17 bars, 16.0 kPa)

3.2 Signals from Microphone and PMT

Shock waves and light emissions from the imploding bubbles were detected by the attached microphone and the PMT respectively. Their signals were displayed and stored by a 100-MHz Agilent™ digital storage oscilloscope. Figure 4 depicts the typical results of these two signals under conditions involving individual clusters. Due to the propagation time required for the sound wave from the location of bubble collapse to the location of the attached microphone on the glass surface, there is a time delay between the microphone signal and the SL signal which is found to be about 30 μs for this chamber. This value corresponds nicely to the time required for a sound wave to travel from the center of the chamber to the walls of the chamber where the microphone is attached. On the other hand, Figure 5 indicates that the corresponding signals are much smaller and random for streamers.

The peak-to-peak amplitudes of the microphone signals were recorded under different driving amplitudes to the PZT ring. The results were depicted in Figure 6. These values indicate the intensities of shock waves generated by the bubble collapse. It can be seen that the shock wave intensity increases with the low acoustic driving amplitudes (implying enhanced levels of implosion) and becomes saturated with increasingly higher drive amplitude. This observation implies that the most intense implosion during cavitation does not necessarily correspond to the highest acoustic driving amplitude.

It was also observed that not every shock wave corresponds to a recorded light pulse. This was found to be especially true for conditions leading to the formation of streamers (which as mentioned earlier look like comets, and consist of thousands of tiny bubbles unlike bubbles in spherical clusters). It was distinctly noted that the presence of streamers did not produce detectable light emission at all, clearly indicating that the intensity of collapse is quite different and much lower (i.e., contents of imploding bubbles were not even hot enough to emit SL light flashes) than that from individual bubble clusters.

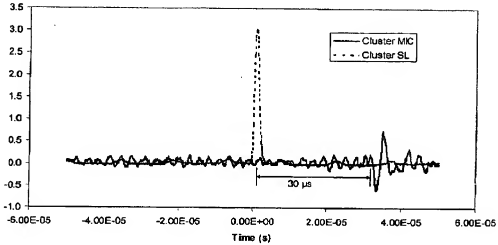

Figure 4: Signals from microphone and PMT of individual cluster

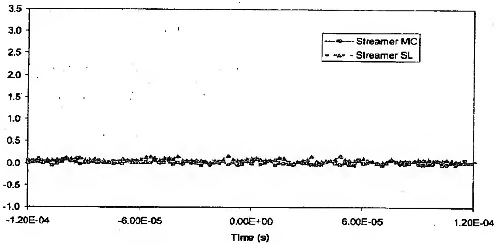

Figure 5: Signals from microphone and PMT of streamers

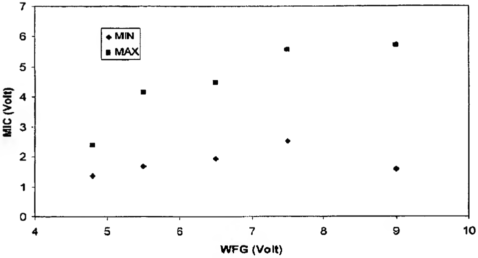

Figure 6: Amplitudes of microphone signals

4. RESULTS OF TRITIUM EMISSION

Similar to the protocol followed for reported bubble fusion experiments (Taleyarkhan et al, 2002, 2004) tests were systematically conducted with deuterated and non-deuterated acetone over six hours duration (to accumulate significant quantities of tritium in the test fluid). The test chamber was positioned in a closed freezer with temperature control, and bubble nucleation was seeded by using a Plutonium-Beryllium (Pu-Be) isotope source (of 1 Ci activity). For each test run lasting for 6h, two samples were systematically prepared by extracting 1 ml of test fluid from the same test chamber before and after each cavitation run and mixing with 15 ml of Ultima Gold™ scintillation cocktail in a 20-ml scintillation vial; therefore, four samples were available for each test run. These samples were analyzed in a scintillation counter for excess tritium emission. The Beckman LS6500™ counter, a sophisticated state-of-the-art system similar to what was used by Taleyarkhan (Taleyarkhan, et al., 2002) was used for these studies. The counter was calibrated with NIST-certified quenched standards and the mass quench effect of acetone was investigated. Each sample was counted over 10 cycles and for 10 minutes during each cycle; therefore, each sample was counted for a total of 100 minutes. There was no interruption for each counting scheme and a sample with 15 ml Ultima Gold™ cocktail alone was also counted simultaneously for validating and ensuring machine stability and for ensuring absence of any unusual background variations.

4.1 Calibration of the Beckman Counter

The Beckman scintillation counter (LS6500) does not directly provide the true measure of radioactive decay in the form of DPM (disintegration per minute). Instead, it conducts a calibration for quenching for each sample (during each cycle) and offers a so-called quench number "H#" along with the raw data for count-rate per minute, i.e., CPM (count per minute) values for each batch. This essentially requires the user to conduct a calibration using known standards (certified by NIST) to obtain the conversion factor from CPM to DPM.

The counter was calibrated with NIST-certified quenched tritium standard vials (procured from PerkinElmer™, 2003). The calibration data were systematically obtained in the same routine as that used for sample counting. The results are shown in Figure 7, where the H# was printed out from the counter accounting for the quenching effect and the efficiencies were calculated from the ratio of the machine CPM and the actual DPM derived from the standards (accounting for radioactive decay).

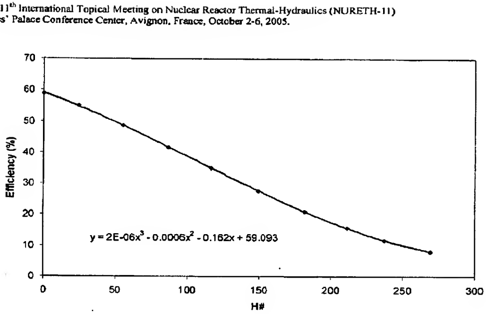

Figure 7: Beckman LS6500 scintillation counter calibration curve. The dots are calibration data points and the solid line is a curve fitting with a third-order polynomial as shown in the figure, which was used to convert the CPM into DPM in tritium counting

4.2 Tritium Counting

Several six-hour duration tests were conducted to confirm if statistically significant quantities of tritium are generated only when conducting neutron-seeded cavitation in C_3D_6O. For these experiments a 1 Ci Pu-Be neutron source (emitting about $2x10^6$ n/s) was available and therefore, utilized. The test cell (maintained at ~ 0°C temperature) was placed in a closed freezer, which was furthermore, surrounded with paraffin blocks for radiological safety. A schematic of the experimental arrangement is shown in Figure 8 along with the relative position of the Pu-Be neutron source. Tests were conducted with neutron irradiation alone, followed by tests with neutron seeded cavitation – systematically changing only one parameter at a time. Neutron-seeded acoustic cavitation was conducted for ~6 h duration. Liquid samples were taken before and after cavitation from the liquid poured into the test chamber. For each case 1 ml of acetone was pippetted and mixed with 15ml of Ultima Gold™ scintillation cocktail in a borosilicate glass vial. These vials were counted for 100 minute for each sample for tritium beta decay activity (5 to 19 keV energy emission window) in a Beckman LS6500™ liquid scintillation counter. Results of tritium activity changes are displayed in Figure 9. It is seen that a statistically significant increase (~ 4 to 6 SD) of tritium is only observed for tests with neutron-seeded cavitation of C_3D_6O. Null results are obtained for all other control experiments. For neutron-seeded cavitation tests with the control liquid C_3H_6O, as well as for tests with neutron irradiation only (without cavitation) of C_3D_6O the tritium activity changes are within 1 SD. Interestingly, one of the four 6h tests (where bubble activity was in the form of streamers, not individual large bubble clusters) with neutron-seeded cavitation of C_3D_6O also gave a null result. This appears to have been due to the occurrence of significant comet-like bubble formations during this particular test. As was mentioned earlier, the presence of streamers also does not give rise to any SL light emission. It is not clear why this particular test gave rise to streamers but the net effect of the change in thermal-hydraulic conditions is unmistakable and goes a long way towards underscoring the importance of attaining appropriate bubble cluster formations to attain bubble fusion.

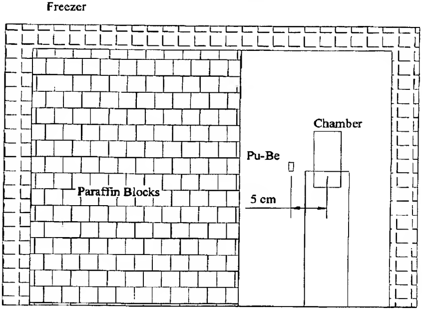

Figure 8: Schematic of experimental apparatus for tritium emission

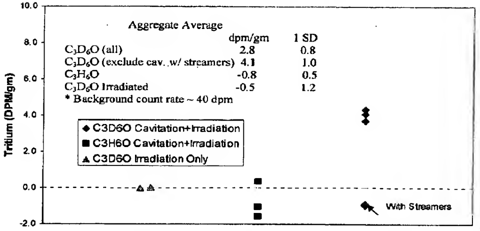

Figure 9: Results of tritium emission counting

5. DISCUSSION AND CONCLUSIONS

Bubble thermal-hydraulics was studied in relation to sonoluminescence light emission and shock wave signals. It was found that strong shock waves from spherical bubble cluster implosions correspond to the generation of significant sonoluminescence light emission, whereas streamer-like bubble formations produce neither distinct shock waves nor sonoluminescence light signals. The bubble cluster lifetime (typically 2 to 5 ms) was much longer than the acoustic driving cycle period (~50 μs) and a contraction was observed at ~0.8 ms, indicating the presence of complex thermal-hydraulic phenomena.

Tritium counting was conducted systematically by using a Beckman LS6500 scintillation counter for the samples obtained from the multiple 6-h bubble fusion experiments with deuterated acetone as well as for the control experiments with non-deuterated acetone. Irradiation only experiments were also performed for deuterated acetone in the presence of the neutron source, but without cavitation. Results of tritium measurements confirmed reported results (Taleyarkhan et al., 2002, 2004a) that the production of statistically significant emissions of tritium occurs only during neutron-seeded acoustic cavitation of deuterated acetone. Control experiments with irradiation alone, and neutron seeded cavitation of non-deuterated (H-bearing) acetone produced null results. The results indicate the possible occurrence of thermonuclear fusion reactions in neutron-seeded acoustic cavitation with deuterated acetone.

NOMENCLATURE

C_3D_6O	Deuterated Acetone
C_3H_6O	Non-deuterated Acetone
D	Deuterium
DPM	Disintegrations per minute
^3He	Helium-3
MIC	Microphone
n	Neutron
p	Proton
PNG	Pulse Neutron Generator
PZT	Lead-Zirconate-Titanate
SD	Standard Deviation
SL	Sonoluminescence
T	Tritium

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